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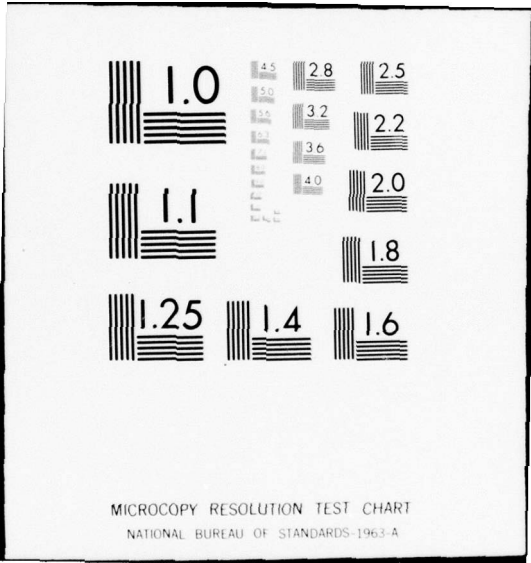
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**MICROPROCESSING TECHNIQUES FOR
ADVANCED SENSORS APPLICATIONS**

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September 1977

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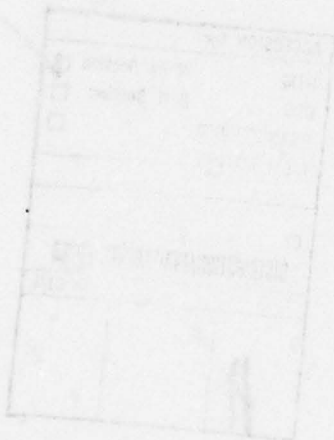
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I. INTRODUCTION

Greater understanding of the theory of digital signal processing coupled with dramatic advances in hardware technology and software engineering has led to improved remote sensing capabilities for military and civilian applications. Nowhere has the impact of theoretical concepts and hardware/software technological advances been felt more than in the field of radar remote sensing. This is due to a large extent to the inherent difficulty of the basic radar signal processing problem.

Radar signal processing differs from other signal processing problems in that very high data throughput rates as well as wide dynamic ranges are often simultaneously required. This unfortunate coincidence results directly from the physics of the remote sensing problem where noncooperative (evasive) target detection using primary radar is hampered by partially correlated noise in the form of ground, weather, and chaff clutter. As a consequence, radar signal processors must be fast (capable of high data throughput rates) and intelligent (capable of executing algorithms which can distinguish between correlated noise and targets of interest). The challenge, then, is to define a radar signal processor which can execute the resulting complex algorithms in real-time with arithmetic precision adequate to allow differentiation between small cross-section targets and large cross-section clutter.

A. Study Objectives

The objective of this study is to investigate the use of microprocessors and other currently available large scale integrated (LSI) circuitry for radar signal processing and to define a structure which is capable of executing algorithms in real-time. A processing throughput objective is provided by the Advanced Sensors Directorate's Quiet Radar parameters [1]. The general processing requirements of this radar serve as a baseline for the present study. While the study is theoretical in nature, the use of these real-world radar parameters tends to anchor the results in a context which can be meaningful in the near-term. In particular, it is envisioned that this study will serve as the basis for the later design and fabrication of a high speed, flexible radar signal processor with a broad range of applications in remote sensing.

A great deal of attention has been focused in recent years on the application of microprocessors to various data processing and control applications. More recently, advances in microprocessor technologies have presented apparent opportunities for increased data throughput and processing flexibility. As a consequence, various processors designed especially for high throughput have been proposed [2-6]. The present task has considered the application of microprocessors as well as other state-of-the-art LSI potentially suitable for use in high-speed signal processing applications.

B. Study Scope

The scope of this work encompasses the basic elements of a radar signal processor architecture analysis at the block diagram level. Tradeoffs are made between candidate approaches as they apply to remote sensing in general and to the Advanced Sensors Directorate's Quiet Radar in particular. It is envisioned that the further reduction of these system level descriptions to fundamental logic circuit diagrams will be accomplished in a related follow-on effort.

C. Study Approach

The approach taken in this study was to investigate signal processor hardware architectures to determine their applicability to the radar processing problem. A basic assumption throughout this study was that existing state-of-the-art LSI including microprocessors and special purpose LSI hardware would be used as the processor building blocks. Analysis of candidate architectures was carried on in light of the baseline signal processing throughput requirements of the Advanced Sensors Directorate's Quiet Radar program but was not restricted to consideration of these parameters only. Consideration was also given to modular architectures which offer flexibility in terms of expansion through replication of constituent components. Such architectures have certain cost advantages as well as robustness in terms of hardware and software reliability and maintainability.

The following discussion presents the study results in a top-down fashion. Candidate classes of signal processor architectures are first discussed. Desirable attributes as well as shortcomings of microprocessor-based signal processors are then considered in relation to the high-speed radar signal processing problem. Succeeding sections relate candidate processor architectures to the baseline radar parameters of interest. Finally, a specific radar signal processor architecture is proposed as a candidate for later detailed design and fabrication.

II. CANDIDATE CLASSES OF SIGNAL PROCESSOR ARCHITECTURES

It is desirable to define a radar signal processor architecture which achieves maximum data throughput and flexibility with a minimum investment in hardware and software. Candidate processing elements to be used in this study are provided by the families of LSI circuits presently available. Of these classes, the following have been considered:

- a) Eight-bit metal oxide semiconductor (MOS) microprocessors.
- b) Four-bit slice microprocessors.
- c) Eight-bit microprocessors + special purpose arithmetic unit.
- d) Special purpose arithmetic hardware.

The performance-related characteristics of devices of this nature are as follows:

- a) Instruction cycle time.
- b) Data word width.
- c) Instruction set.
- d) Small scale integration/medium scale integration (SSI/MSI) overhead required.
- e) Bus structure.
- f) Input/Output (I/O) capabilities.

The performance characteristics were considered for each of the previously listed classes of microprocessor architectures. The following sections consider three specific classes of processor architectures.

A. Single Microprocessor Architectures

Previous works on multiprocessing systems have defined single central processing unit (CPU) computers as "Single-Instruction Single Data (SISD)" machines [7]. The majority of the general purpose computers presently in use are SISD architectures. SISD architectures use a single-control unit to route data into and out of the CPU. As a result only one arithmetic process such as addition, subtraction, multiplication, or division can occur at one time. Furthermore, the movement of data is usually accomplished by means of a single data bus in such designs.

The primary advantage of single-instruction single data architectures is the simplicity of the hardware and software structures. These machines require little in the way of hardware and are straightforward to program. Unfortunately, these attributes are achieved at the expense of data throughput and flexibility as demonstrated in later sections of this report. However, the SISD class processor remains important because it is the primary building block of more complex processors.

1. Non-Bit Slice Processors

A microprocessor which illustrates the SISD architecture is the Intel 8080A, 8-bit machine. For purposes of this study, the 8080A has been chosen as the baseline architecture to which other designs may be compared. Specifically, the 8080A was chosen for the following reasons:

- a) It is the most widely used microprocessor.
- b) It is low-cost and readily available.
- c) It is reasonable to consider an array of such machines in more complex architectures.

Unfortunately, the single data bus structure permits only limited data flow. Obvious variations of this basic structure therefore include multiple operational and resultant buses to permit increased flexibility in terms of data management alternatives.

2. Bit-Slice Processors

Attempts to achieve higher data throughput rates with programmable LSI have resulted in the creation of bit-slice microprocessor devices. The primary advantage of these devices is their faster instruction cycle time. Their major disadvantages include increased part counts due to support circuit requirements and the fact that they are generally harder to program. Bit-slice microprocessors have been used in two primary application areas as follows:

- a) As instruction set emulators where microprogrammed bit-slice machines are made to look like other processors.
- b) In moderate speed signal processing applications where advantage can be taken of their micro-instruction power and faster instruction execution time.

Bit-slice processors using the Motorola M10800 have been designed by Motorola [8], Raytheon [9], and others. These machines have instruction cycle times on the order of 100 nsec.

Another bit-slice microprocessor is the Advanced Micro Devices (AMD) AM2900, 4-bit-slice device. This processor uses Schottky bipolar LSI technology and executes instructions at a rate of approximately 250 nsec. Although the AM2900 cycle time is slower than the M10800, it is generally easier to program because the AM2900 is a 2-bus structure while the M10800 is a 3-bus design. Thus, more options and potentially more powerful instructions are available with the M10800.

At the present time, greater software support is available with the AM2900 including a cross-assembler. However, Motorola is in the process of developing a software support package for the M10800 which should be available by the end of the calendar year.*

*Balph, Tom, Motorola, Inc., Phoenix, Arizona, September 1977 (Private Communication).

Finally, a third bit-slice microprocessor has recently become available. This machine differs from the others in that it is an 8-bit-slice device. The part has been introduced by RCA and is known as the ATMAC microprocessor. Unfortunately, this device is not available as a commercial component but may be purchased only from RCA as a part of a system. On the positive side, RCA does have extensive documentation and software support available [10-12]. The ATMAC is attractive to the signal processor designer for the following reasons:

- a) It combines low power with high speed by using complementary metal oxide semiconductor/silicon-on-sapphire (CMOS/SOS) technology to give a very low speed-power product.
- b) It is an 8-bit-slice (versus a 4-bit-slice) device and therefore requires fewer components to realize a total system.
- c) It has provisions for a peripheral special function unit (SFU) which can be a high-speed multiplier device, for example.

Unfortunately, the ATMAC 8-bit-slice microprocessor data throughput is limited by the incorporation of only a single bus I/O structure. This appears to be its greatest architectural weakness. Discussions with RCA personnel generally confirm this limitation.*

B. Multi-Microprocessor Architectures

Arrays of low-cost microprocessors performing multiple computational tasks in parallel have been considered as an alternative for achieving higher data throughput rates in radar signal processing applications. The obvious advantage of such an approach is the redundancy inherent in such a design which can lead to a more survivable processor in case of component failures. The obvious disadvantage of this approach is the difficulty in programming such a structure.

Arrays of 8-bit MOS microprocessors are potentially more attractive than arrays of 4-bit-slice bipolar designs because of the lower parts count and generally lower cost of the 8-bit processors. Unfortunately, the 8-bit devices have a single I/O bus while the 4-bit parts have one or two operand buses and a resultant bus.

C. Task-Allocated Processor Structures

In radar signal processing, various tasks of differing complexity and speed must be performed. One possible way to arrive at a radar signal processor architecture is to determine the needs of each processing subtask and to create the required computational resources necessary to accomplish those tasks. This approach will be referred to in this discussion as "task-allocated" signal processing.

*Helbig, Walter, RCA Advanced Technology Laboratories, Camden, New Jersey, August 1977 (Private Communication).

At the crux of the radar digital signal processing problem are the high data throughput requirements. Therefore, a logical place to begin in defining a task-allocated structure is with those subtasks which have the most demanding throughput requirements. In most coherent radars, filtering operations require the greatest number of arithmetic operations in the shortest time interval. These operations generally consist of:

- 1) High-pass filtering — Moving Target Indication (MTI).
- 2) Low-pass filtering (clutter maps).
- 3) Band-pass filtering (Doppler filtering).

The high-pass and low-pass filters may be synthesized using well-known finite impulse response (FIR) and infinite impulse response (IIR) techniques [13-15]. The band-pass filters required for Doppler processing are usually realized with the fast Fourier transform (FFT) algorithm [14, 15].

The top-down approach taken in this study was to determine how fast various microprocessor and special purpose hardware structures could perform the required computations necessary to accomplish these filtering operations. Filter order (weights) and transform length were used as parameters of interest. A priori knowledge of the Quiet Radar performance requirements were used to determine approximate filter orders and transform lengths of interest. Arithmetic precision was initially assumed to be 16-bits. It is expected that further work will be performed to determine the validity of this assumption.

The first task to be considered is that of MTI filtering. Such filters may be realized as either conventional N-pulse cancellers which require that

$$y_n = a_0 X_n - a_1 X_{n-1} - \dots - a_{n-1} X_{n-1} \quad , \quad (1)$$

where $X_n = N^{\text{th}}$ input data word. In the simplest case, the coefficients, a_i , are unity. Thus, the simplest two-pulse canceller requires only a single subtraction for each return pulse.

More sophisticated MTI filters may be realized using FIR synthesis techniques. Furthermore, FIR designs can be high-pass, low-pass, or band-pass, depending upon the coefficients selected. Figure 1 presents the computational requirements of an FIR design. The structure depicted in this figure computes

$$y_n = \sum_{k=0}^K a_k X_{n-k} \quad . \quad (2)$$

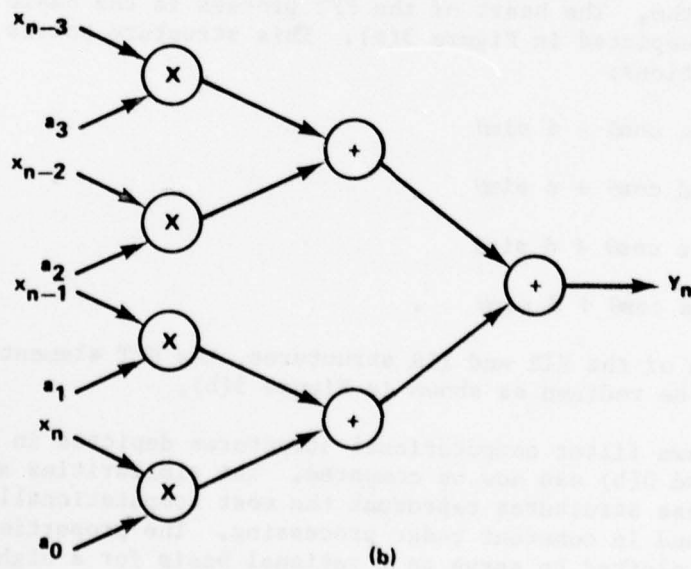
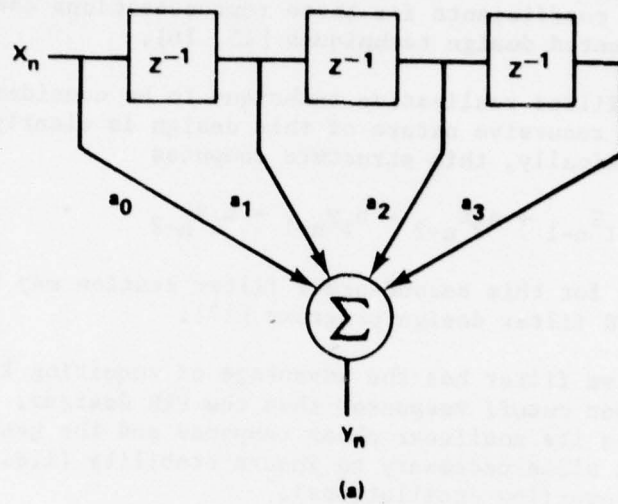


Figure 1. FIR digital filter.

The structure depicted in Figure 1(a) may be redrawn as shown in Figure 1(b). The usefulness of this representation will be shown later in this discussion. The coefficients for these representations can be determined using well-documented design techniques [15, 16].

The second filter realization technique to be considered is the IIR filter. The recursive nature of this design is clearly illustrated in Figure 2. Basically, this structure computes

$$y_n = x_n + a_1 x_{n-1} + a_2 x_{n-2} - b_1 y_{n-1} - b_2 y_{n-2} \quad (3)$$

The coefficients for this second-order filter section may be determined from existing IIR filter design programs [17].

The recursive filter has the advantage of requiring lower orders to achieve sharper cutoff responses than the FIR designs. Its major disadvantages are its nonlinear phase response and the generally greater coefficient word sizes necessary to insure stability (i.e., to minimize limit cycle and overflow oscillations).

As in the case of the FIR filter, the IIR representation shown in Figure 2(a) may be redrawn as illustrated in Figure 2(b). Again, the usefulness of this exercise will become apparent in the later discussion.

The third filter to be considered is the band-pass filter. Band-pass filters for radar Doppler processing are frequently realized using the FFT algorithm. The heart of the FFT process is the basic computational element depicted in Figure 3(a). This structure solves the following equations:

$$\begin{aligned} a' &= a + c \cos\theta - d \sin\theta \\ b' &= b + d \cos\theta + c \sin\theta \\ c' &= a - c \cos\theta + d \sin\theta \\ d' &= b - d \cos\theta + c \sin\theta \end{aligned} \quad (4)$$

As in the case of the FIR and IIR structures, the FFT elemental computations may be redrawn as shown in Figure 3(b).

The redrawn filter computational structures depicted in Figures 1(b), 2(b), and 3(b) can now be compared. The similarities are quite apparent. These structures represent the most computationally demanding algorithms found in coherent radar processing. The properties evident here can be exploited to serve as a rational basis for a high-speed radar signal processor design as shown in the following discussion.

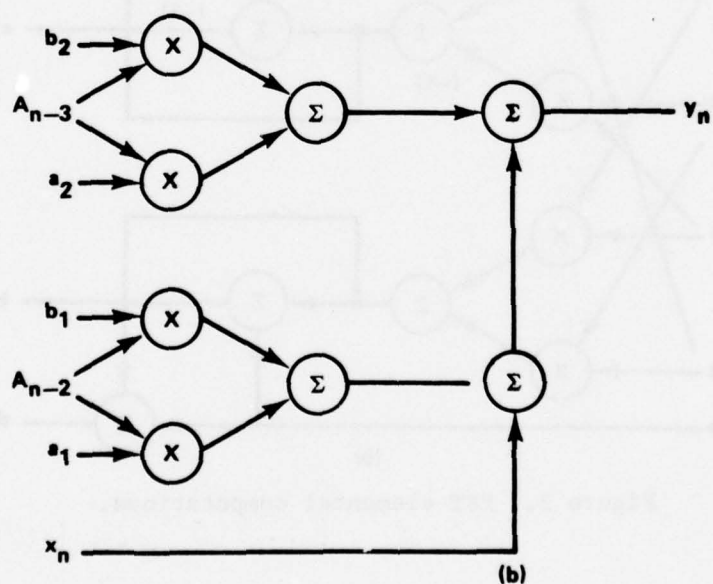
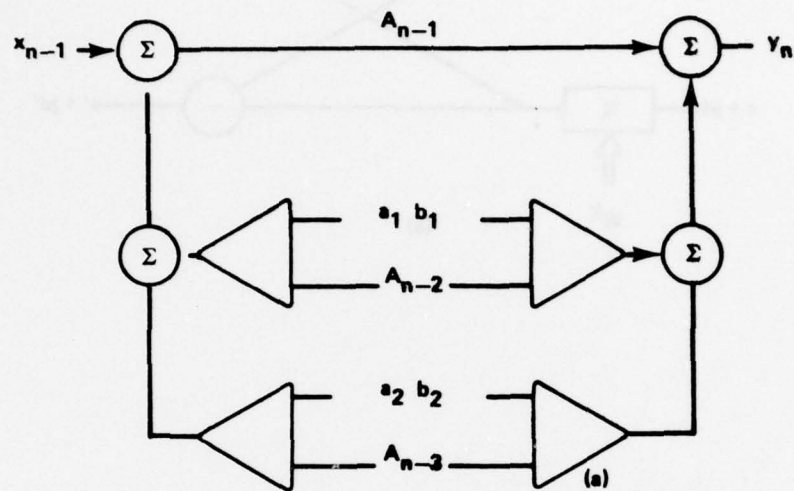


Figure 2. IIR digital filter (second-order section).

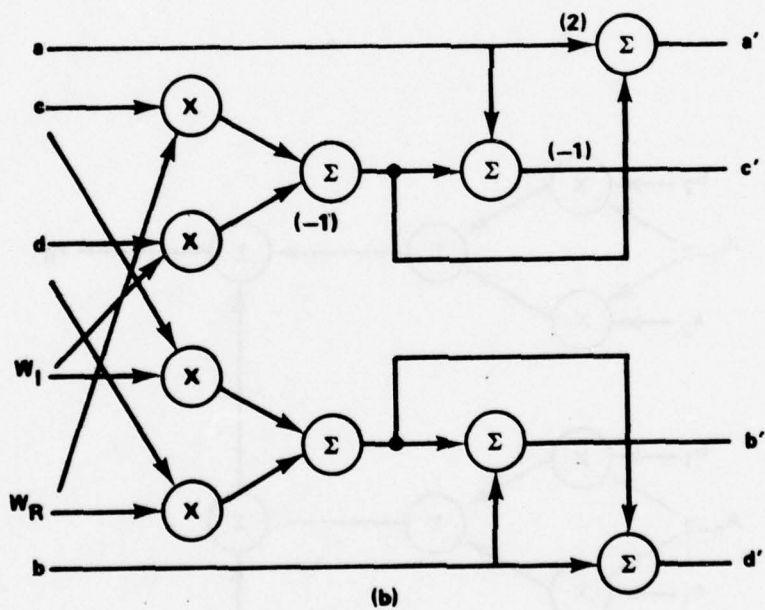
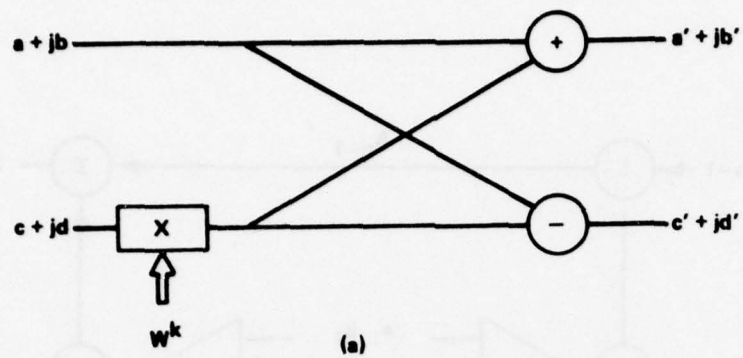


Figure 3. FFT elemental computations.

The arithmetic elements common to the redrawn FIR, IIR, and FFT structures are four multipliers and several adders. Therefore, taking the union of the three configurations shown in Figure 1(b), 2(b), and 3(b) and minimizing the functional arithmetic elements results in a basic signal processing structure which can accommodate the high throughput algorithms required by coherent radars. Two important questions are (1) how to route the data efficiently to and from the high-speed computational elements, and (2) how to store and buffer I/O and partial result data effectively.

The approach taken to data routing in the proposed special purpose processor is to use multiple parallel data buses to avoid the common problem of bus-limited data transfers. Such an approach has the potential for achieving 100% computational efficiency by supplying data continuously to the arithmetic computational elements.

The problem of special purpose processor data storage can be met with high-speed, distributed memory capable of accepting data in parallel from multiple buses. An important advantage of distributed memory, in addition to having multiple I/O ports available to accommodate pipelined data, is the ability to do data steering (switching) by clever memory addressing techniques. If the special purpose processor arithmetic unit is envisioned as a miniswitching system, the data storage elements can be used in much the same way as in large electronic switching systems such as the Bell System's Electronic Switching Systems (ESS) machine.

The final important concept to be discussed briefly in addition to arithmetic, data-bus, I/O, and memory is that of special purpose processor control. To achieve maximum flexibility and to guarantee that the resulting structure will compute the FIR, IIR, FFT, and other signal processing algorithms efficiently, it is proposed that the basic control be microprogrammable. In a signal processing structure such as that proposed here, the microprogram object code may be thought of as data switch enables/disables. Thus, the data steering function is controlled by the processor microprogram. The microprogram itself can reside either in Read-Only-Memory (ROM), assuming that all processing algorithms to be executed are known a priori or it can reside in Random Access Memory (RAM) which can be loaded by a more intelligent machine such as a microprocessor or minicomputer.

The union of all the ideas briefly outlined in the preceding paragraphs have been incorporated in a proposed radar signal processing structure which is illustrated in Figure 4. It is proposed that the special purpose arithmetic unit be constructed of computational and memory components which will permit a 200-nsec pipelined throughput. Under the assumption that such a processor can be constructed, the resulting FIR, IIR, and FFT data throughput rates as a function of filter order and FFT transform length can be determined.

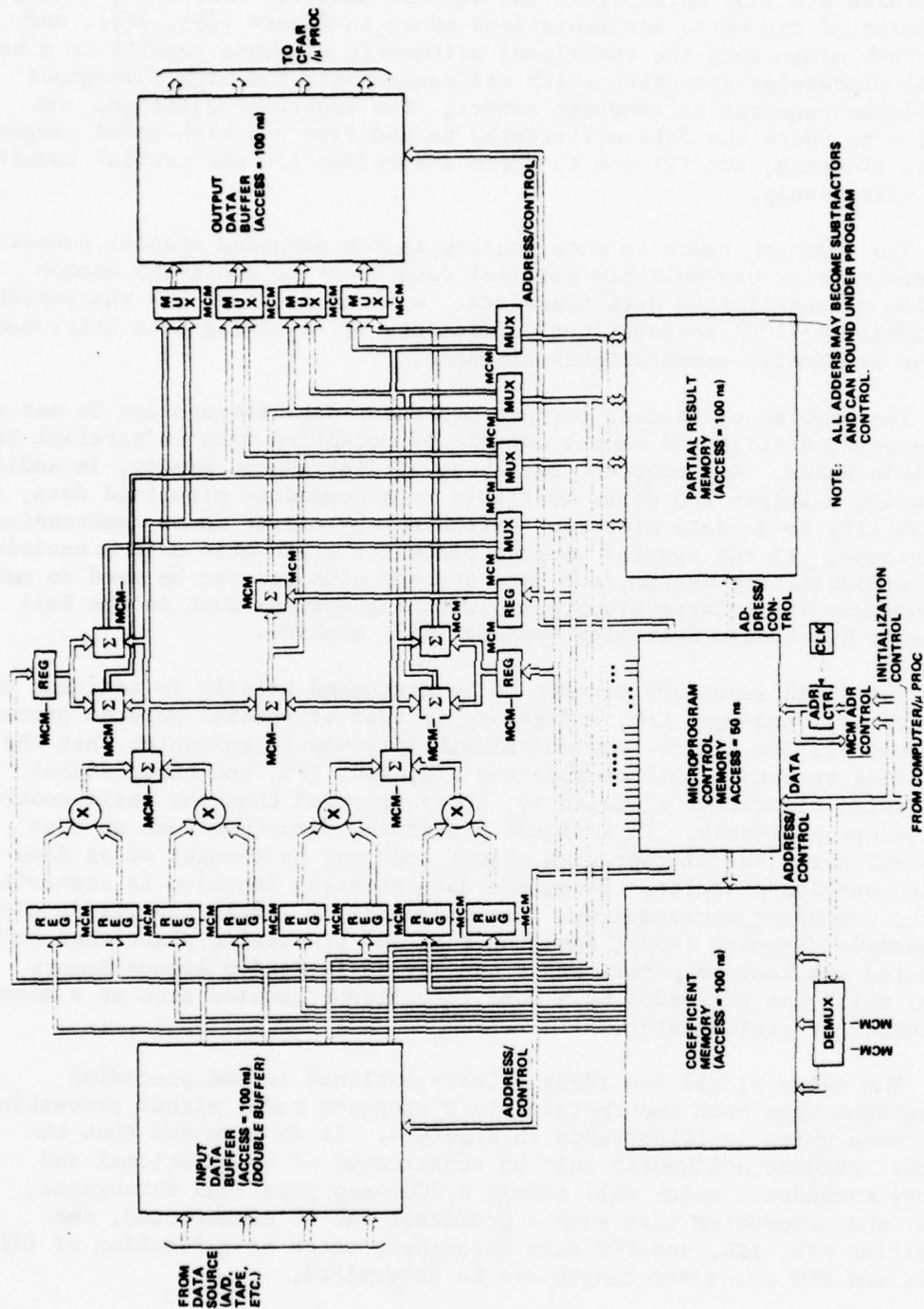


Figure 4. Proposed radar signal processor arithmetic unit.

III. BASELINE PROCESSING REQUIREMENTS

The baseline processing requirements for this study are provided by the Advanced Sensors Directorate's Quiet Radar. This is a phase-coded continuous wave (CW) radar with the following characteristics:

- a) Code shift rate = 5 MHz.
- b) Code length = 63 bits.
- c) Antenna dwell time = 2 msec.
- d) Number of Code Periods per dwell = 150.
- e) Doppler Coverage = ± 25 kHz.
- f) Number of Doppler lines = 100.

A number of specific Quiet Radar processor configuration alternatives have been carefully considered by the US Army Missile Research and Development Command (MIRADCOM) and therefore will not be iterated here. The important parameters to note are the code shift rate (5 MHz), the antenna dwell time (2 msec) and the Doppler cutoff frequency (25 kHz).

Based upon a processing interval of 2 msec and 63 range cells/dwell, the per range cell computation interval is $31.7 \mu\text{sec}$ complex or $15.8 \mu\text{sec}$ per real channel. This computation interval may be compared to the times required to compute various orders of FIR, IIR, and FFT transform lengths discussed in the following sections.

IV. REQUIREMENTS VERSUS SIGNAL PROCESSOR ARCHITECTURE TRADEOFFS

With the Quiet Radar processing requirements as a reference point, the signal processor architectures described earlier may be considered. The following sections discuss single processors, multiprocessors, and the task-allocated signal processor approaches.

A. Single Processors

The single microprocessors considered in this study were the 8-bit MOS, 4-bit-slice bipolar, and 8-bit-slice CMOS/SOS devices. To determine their suitability for computing the signal processing algorithms discussed earlier, i.e., the FIR filter, IIR filter, and FFT, these algorithms were either encoded and implemented to provide benchmark timing requirements or, where possible, were taken from the literature.

The Intel 8080A, which has become an industry standard 8-bit microprocessor was chosen to provide a baseline upon which the other approaches may be compared. This is a reasonable choice because many versions of the 8080A exist in the form of high-speed bipolar emulators as well as software upward compatible, higher speed devices such as the Z-80 microprocessor.

Figure 5 depicts the 8080A baseline throughput capability for three possible configurations. These configurations are as follows:

- 1) 8080A with software multiply.
- 2) 8080A with the AMD AM9511 arithmetic processor chip.
- 3) 8080A with a high-speed peripheral multiplier such as the TRW single chip devices.

As could be anticipated, the 8080A with software multiply only is by far the slowest configurations. For example, this configuration requires approximately 10 msec to compute a 16-weight FIR filter. The details of the 8080A configuration and the software used establish this benchmark are given in Appendices A and B of this report.

Figure 5 shows that a half-order magnitude speed-up can be achieved using the 8080A augmented with the AMD arithmetic unit (AM9511). The configuration used is described in detail in Appendix A.

The third 8080A configuration considered was the 8080A coupled with a high-speed multiplier. This configuration results in a throughput increase which is close to an order of magnitude faster than the 8080A with software multiply. It is significant that the increase in throughput achieved by the 8080A with the high-speed multiplier relative to the 8080A with the AMD device is not as great as expected. The fundamental reason for this is that as the peripheral devices become faster, the basic throughput limitation becomes I/O bound. This is true in the 8080A case even with memory mapped I/O.

It should be pointed out that faster versions of the 8080A would shift these curves down in a corresponding manner. Additional speed-up could also be achieved with an expander instruction set such as that available with the Z-80. However, as seen later in this discussion, the overall throughput increase would not be consequential relative to most coherent radar processing requirements.

Two additional single processor architectures were considered for reference. The first of these is the Motorola MOD System which is basically an 8-bit processor composed of two-slices of the M10800 microprocessor [8]. Its performance, assuming the use of Booth's algorithm to perform the software multiplies is shown in Figure 5.* It can be observed that for the FIR algorithm, the throughput can be increased by a factor of 10 over the baseline 8080A using Booth's algorithm. However, it is important to recall that this increased throughput is achieved at the expense of the much higher component parts count required by bit-slice microprocessors as well as more complex software.

*Balph, Tom, Motorola, Inc., Phoenix, Arizona, September 1977 (Private Communication).

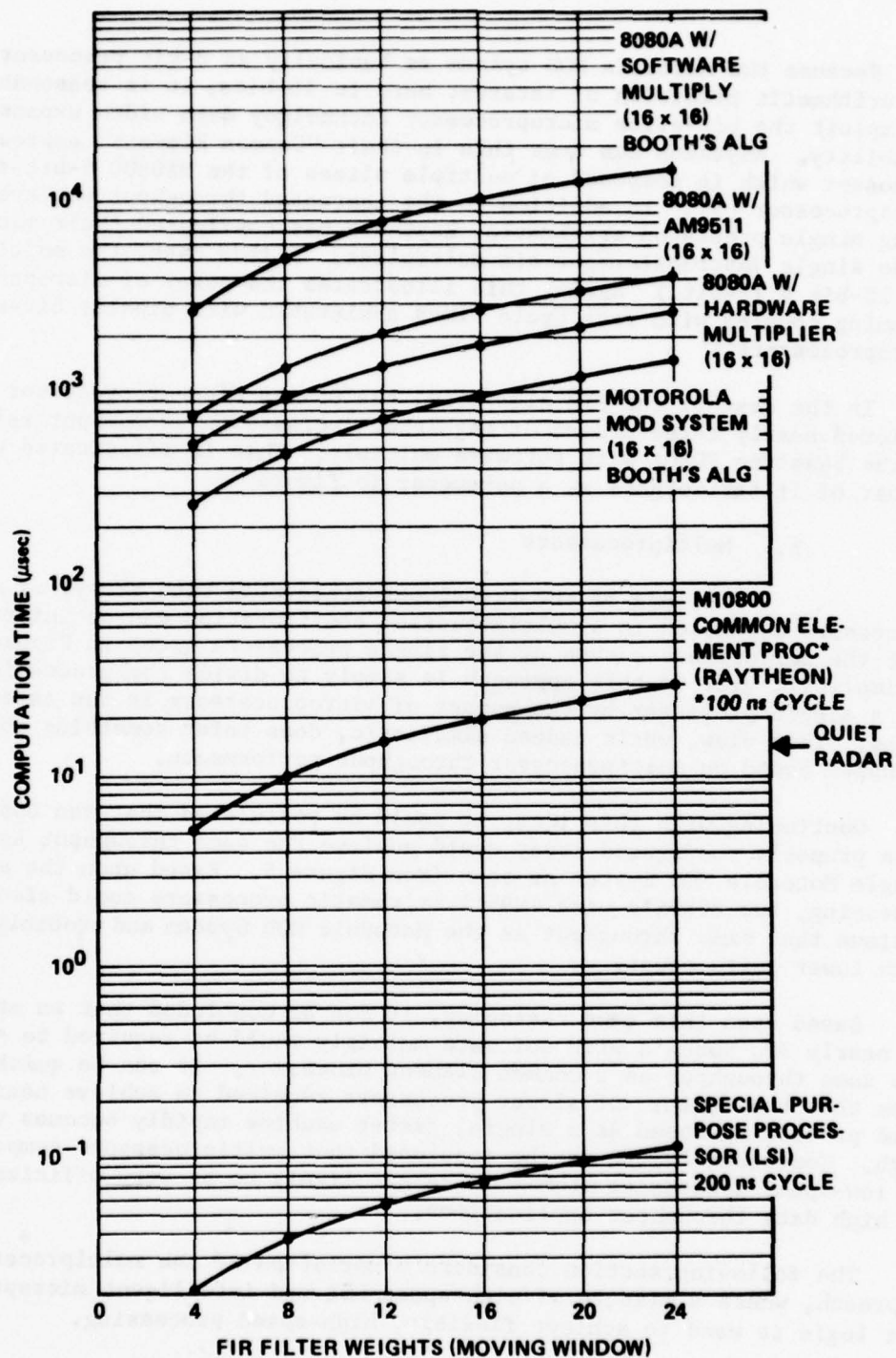


Figure 5. FIR filter throughput.

Because the Motorola MOD system is basically an 8-bit processor and the arithmetic precision of interest here is 16-bits, it is reasonable to exploit the bit-slice microprocessor technology data width expansion capability. Raytheon has done this in their "Common Element" approach processor which is composed of multiple slices of the M10800 4-bit-slice microprocessor [9]. In addition to the increased throughput achieved by doing single precision arithmetic, Raytheon has configured their machine to do single instruction-per-bit multiplies. In this case, the multiplies are 12-bit \times 12-bit.) Again, this illustrates the power of microprogramming coupled with fast cycle times achievable with bipolar bit-slice microprocessors.

In the case of the FIR algorithm, the Common Element processor achieved nearly three orders of magnitude increase in throughput relative to the baseline 8080A with software multiply. This is illustrated with number of filter weights as a parameter in Figure 5.

B. Multiprocessors

An idea of the throughput achievable with arrays of microprocessors assembled in a multiprocessor configuration can be inferred from the performance curves of the single processors given in Figure 5. A simplistic view of this approach is simply to divide the processing time for a single processor by the number of microprocessors in the assembled array. This view, while indeed simplistic, does infer something about an upper bound on multiprocessor throughput performance.

Continuing with this idea, it could be postulated that ten 8080A's in a properly configured array could achieve the same throughput as a single Motorola MOD System as seen from Figure 5. Based upon the same reasoning, two 8080A's with AM9511 arithmetic processors could also achieve the same throughput as the Motorola MOD System and probably at a much lower parts count.

Based upon this same reasoning, it can be concluded that an array of nearly 300 8080A's with software multiply would be required to achieve the same throughput as a Common Element processor. It can be quickly seen that the number of slower processors required to achieve nearly the same processing speed as a single, faster machine rapidly becomes very high. Consequently, it can be concluded that multiprocessors composed of low-speed processing elements are not likely to be very efficient in high data throughput applications.

The following section considers a variation of the multiprocessor approach, where a mixture of high-speed LSI and intelligent microprocessor logic is used to achieve flexible, high-speed processing.

C. Task-Allocated Processing

The lower bound on data throughput for purposes of this study is achieved by the special purpose radar processor described in Section II.C. Figure 5 illustrates that such a design can potentially realize data throughput rates which are four to five orders of magnitude faster in computing the FIR algorithm than the baseline 8080A processor discussed earlier (Section II.A and Appendices A and B). The fact that the proposed special purpose processor is approximately two orders of magnitude faster when computing the FIR algorithm than the M10800 Common Elements approach proposed by Raytheon is illustrated in Figure 5. Viewed another way, this says that if 100 Common Element processors are required to achieve the necessary data throughput, only one special purpose processor can replace all 100 Common Element processors.

The central issue here is obvious tradeoff between processor data throughput and processor flexibility. However, a great deal of flexibility can be achieved with a special purpose arithmetic unit through the use of programmable control. The control structure of the processor shown in Figure 4 essentially performs a data routing role. Thus, by making these operations microprogrammable, the special purpose unit can be made to perform a large number of different algorithms and thereby overcome processor flexibility limitations. It is proposed that additional work be undertaken to define specifically the nature of this control structure. One possibility which should be studied further is the incorporation of a microprocessor to perform such control functions.

A second potential application for a microprocessor in a task-allocated structure is as a post-processor. That is, after the high-speed algorithm processing has been accomplished by the special purpose LSI (i.e., the multipliers, adders, high-speed memory, etc.) more sophisticated, but lower throughput, processing is usually required. For example, Constant False Alarm Rate (CFAR) processing with associated thresholding and clutter map generation may be accomplished in a moderate-speed microprocessor. This area is also identified as one where additional work is needed.

Figure 6 represents the same benchmark approach to processor comparison illustrated in Figure 5 except that Figure 6 is for the IIR algorithm. The two figures are similar, but results are given for different filter orders. A comparison of the FIR and IIR algorithms shows that the basic memory access required for each is first-in, first-out (FIFO). In addition, it has already been shown that the computational elements themselves are similar (Figures 1 through 3). Therefore, it is reasonable for the benchmark throughput results to be similar.

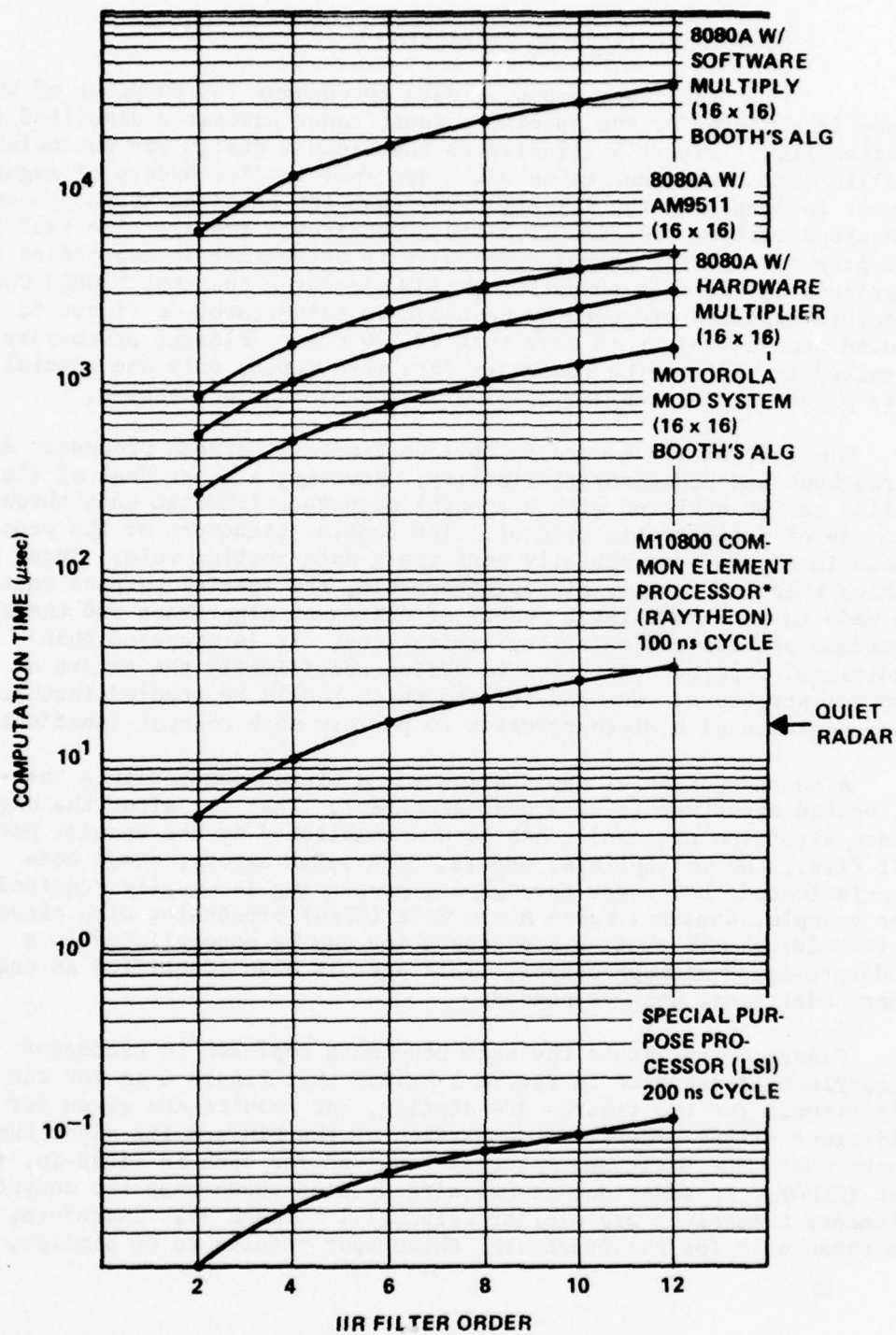


Figure 6. IIR filter throughput.

The most computationally demanding coherent radar processing algorithm is the band-pass Doppler filtering often accomplished using the FFT algorithm. Figure 7 presents the results obtained using the signal processor configurations described earlier. The length transforms considered were from 8 to 256 points. Earlier work has shown that realistic transform lengths for the Quiet Radar are from 64 to 256 points.*

It can be observed from Figure 7 that for a 128-point transform, for example, the special purpose processor is nearly four orders of magnitude faster than the baseline 8080A processor with software multiply. As in the case of the FIR and IIR algorithms, the bit-slice processors fall between these bounds. One additional interesting FFT benchmark shown in Figure 7 is the RCA 8-bit-slice ATMAC processor with SFU [18].

The throughput achieved with the RCA device is comparable to that achieved with the Raytheon Common Element approach in the case of the FFT algorithm. However, this throughput is achieved with a lower parts count because the ATMAC represents a higher level of circuit integration (i.e., 8-bit-slice versus 4-bit-slice). Details of this processor are given in References 6 and 10.

V. RECOMMENDATIONS AND CONCLUSIONS

The general problem of realizing a flexible, high throughput signal processor for coherent radar applications has been considered. The approach taken in this study has been to investigate various microprocessor configurations and to evaluate their capabilities through the use of benchmark radar signal processing algorithms. As a baseline configuration, the popular 8080A microprocessor was chosen. Various configurations of the 8080A with software multiply only and versions of the 8080A augmented with special peripheral arithmetic hardware were considered. The signal processing algorithms of interest were programmed on these machines and their throughput capabilities determined. Both the AMD AM9511 arithmetic processor and a high-speed peripheral multiplier were used to augment the basic 8080A.

The ability of bit-slice microprocessors to process the benchmark coherent radar algorithms was evaluated as a part of this study. The particular 4-bit microprocessor considered was the faster cycle time device currently commercially available, namely, the Motorola M10800. The two configurations evaluated and compared to the baseline 8080A processor were the Motorola MOD System and the Raytheon Common Element processor. Where data were available, the RCA 8-bit ATMAC processor was also considered.

*Burlage, Don, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, September 1977 (Private Communication).

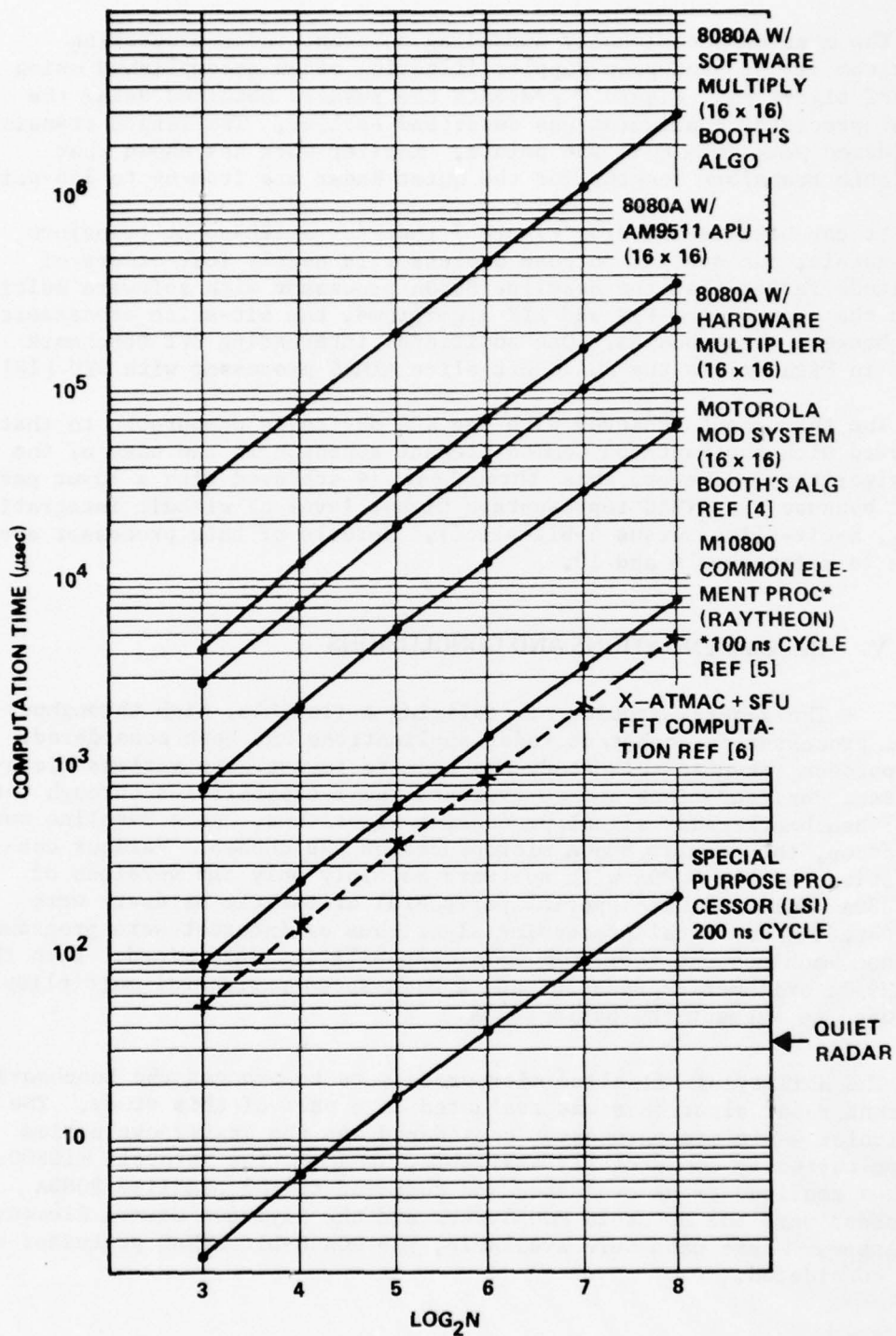


Figure 7. FFT throughput.

Finally, a high-speed arithmetic unit comprised of special purpose LSI circuitry was configured and its throughput capabilities evaluated. The rational basis for this design was the similarity of the coherent radar signal processing algorithms of interest. The throughput performance of the single processors, multiprocessors, and task-allocated processors were considered with filter order and transform length as parameters.

The major conclusion of this study is that a carefully configured combination of high-speed, special purpose LSI coupled with distributed intelligence in the form of microprocessors can effectively meet the throughput and flexibility requirements of coherent radars. More specifically, it has been determined that such an embodiment can meet the processing needs of the Quiet Radar. It is therefore recommended that additional work be undertaken to answer remaining performance questions and that following this effort, such a processor be constructed and interfaced with the Quiet Radar.

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Appendix A. 8080A PROCESSOR BENCHMARK CONFIGURATIONS

The equation solved by the FIR class of digital filters is

$$y_n = \sum_{k=0}^K h_k x_{n-k} \quad (A-1)$$

where h_k are the filter coefficients and x_n are the samples. From this expression, it is seen that two tables are required: one for storing the coefficients h_k , and one for storing x_{n-k} . The table for the coefficients could be ROM or RAM; however, the table for x_{n-k} is RAM and as will be shown later, preferably a K level circulating FIFO. If RAM is used, then this FIFO is implemented by software.

The coefficients are stored as 16-bit two-complement numbers. The samples are 8-bit two-complement numbers. Hence, the need for a 16- by 8-bit multiplier. This multiplier will be implemented presently by software.

The algorithm necessary for the computation of y_n is straightforward. A flowchart is given in Figure A-1. The software multiply algorithm chosen for implementation in the 8080A processor is the well-known Booth's algorithm. While more efficient mechanizations may be known, this algorithm is representative. The following discussion briefly describes Booth's multiplication procedure.

In two-complement form, X can be represented as

$$X = -2^n x_n + \sum_{m=0}^{n-1} 2^m x_m$$

and Y can be represented as

$$Y = -2^m y_m + \sum_{j=0}^{m-1} 2^j y_j$$

or

$$Y = (y_{m-1} - y_m) 2^m + \sum_{j=0}^{m-1} 2^j (y_{j-1} - y_j) y_{-1} = 0 \quad ;$$

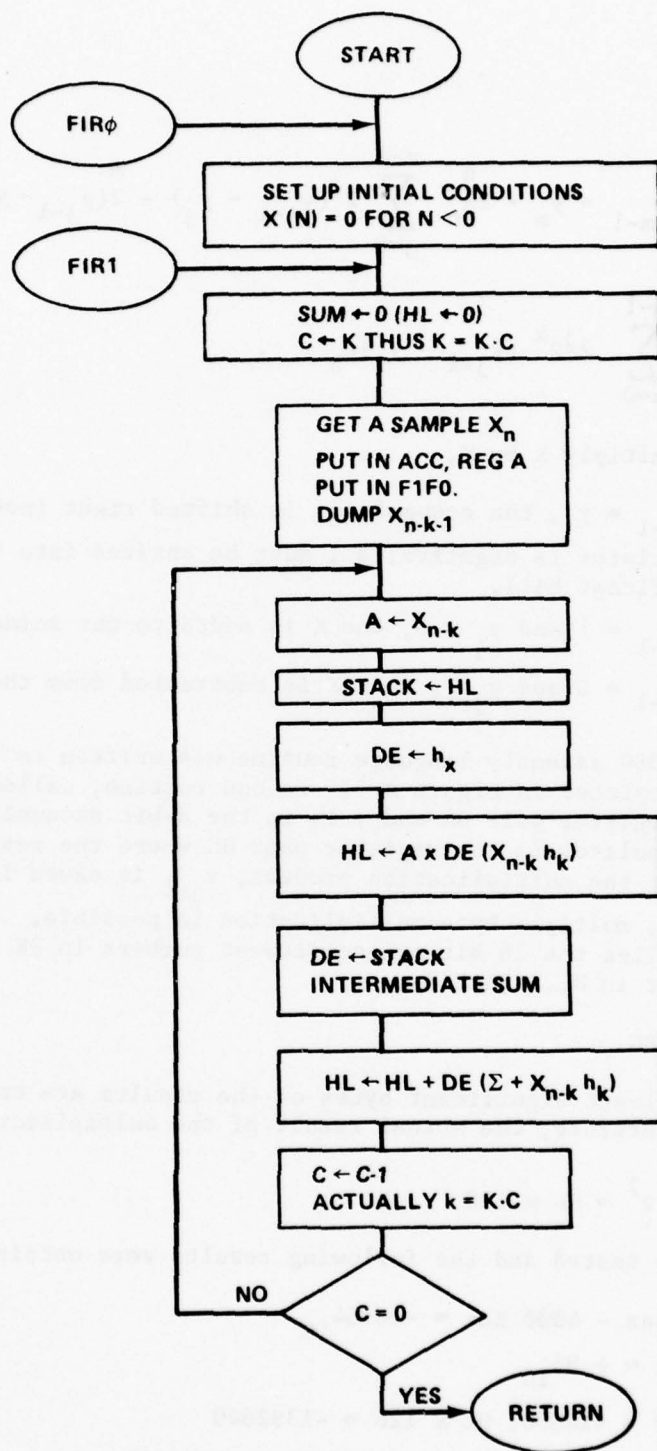


Figure A-1. FIR filter algorithm flow chart.

then,

$$\begin{aligned}
 XY = & 2x_n (y_{m-1} - y_m - 2x_n \sum_{j=0}^{m-1} 2^j (y_{j-1} - y_j) - 2(y_{j-1} - y_j) \sum_{k=0}^{n-1} 2^k t_k \\
 & + \sum_{j=0}^{n-1} \sum_{k=0}^{n-1} 2^{j+k} (y_{j-1} - y_1) n_k .
 \end{aligned}$$

Therefore, to multiply X by Y,

- 1) If $y_{j-1} = y_j$, the accumulator is shifted right (not if the accumulator is negative; a 1 must be shifted into the most significant bit).
- 2) If $y_{j-1} = 1$ and $y_j = 0$, the X is added to the accumulator.
- 3) If $y_{j-1} = 0$ and $y_j = 1$, then X is subtracted from the accumulator.

An Intel 8080 assembly language routine was written to implement the algorithm depicted in Figure A-2. In one routine, called MULT, x is stored in the register pair DE and y is in the 8-bit accumulator, A. The 16-bit accumulator is the register pair HL where the result is obtained. After the multiplication process, y_{j-1} is saved in the carry bit. Therefore, multiple byte multiplication is possible. The routine, MULT 16, multiplies the 16-bit two-complement numbers in DE and BC and forms the result in HL. That is,

$$HL \leftarrow DE \times BC.$$

The seven least significant bytes of the results are truncated using MULT. Therefore, the actual result of the multiplication is

$$xy = HL \times 2^7 = HL \times 128 .$$

The routine was tested and the following results were obtained:

$$x = C000 \text{ Hex} - 4000 \text{ Hex} = -16384_{10}$$

$$y = 55 \text{ Hex} = + 85_{10}$$

$$HL = D580H = -2A80H; HL \times 128 = -1392640$$

$$\text{Check: } 85 \times (-16384) = -1392640$$

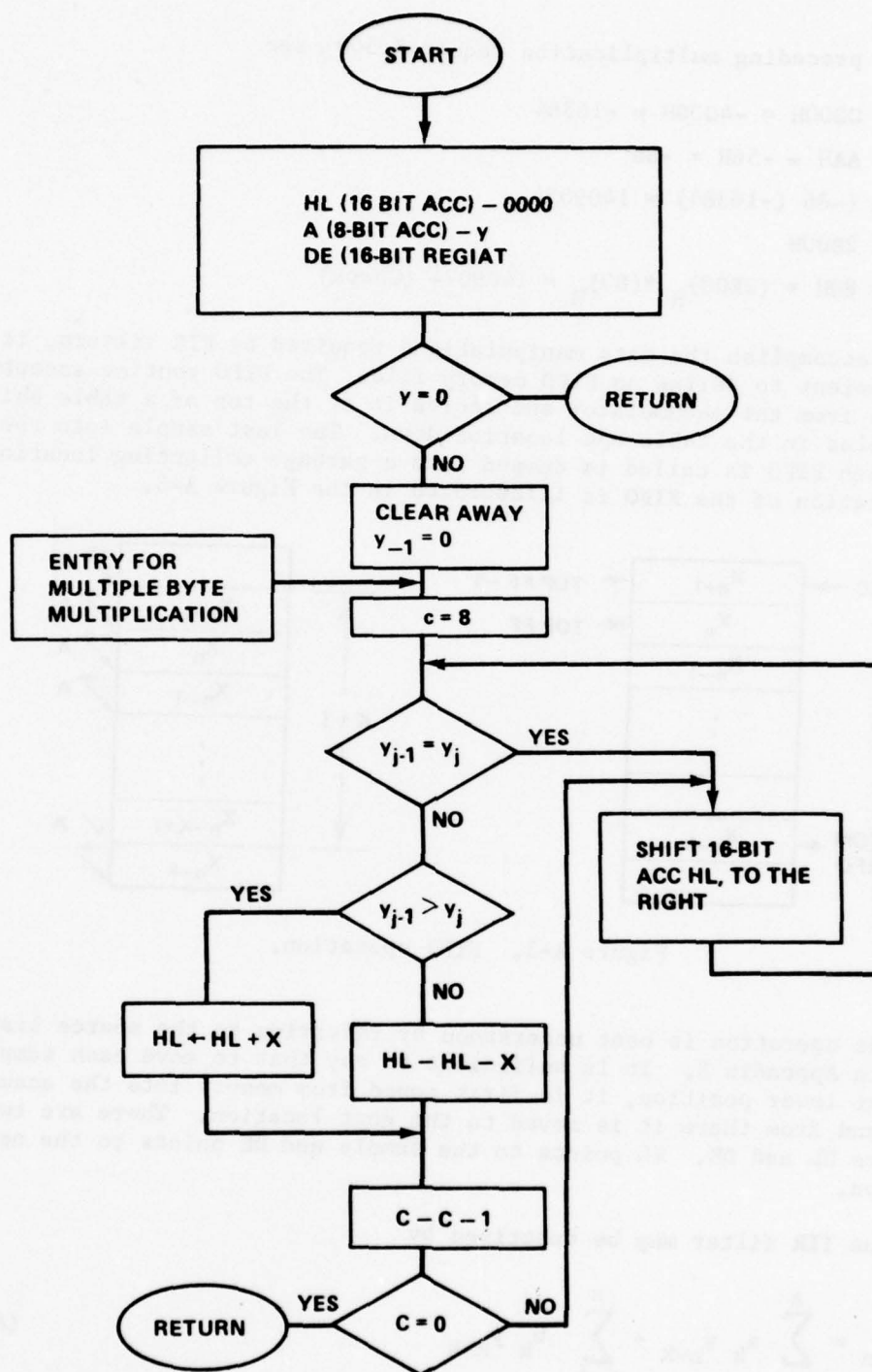


Figure A-2. Multiplication algorithm (16 × 18).

The preceding multiplication required 500 μ sec

$$x = C000H = -4000H = -16384$$

$$y = AAH = -56H = -86$$

$$xy = (-86)(-16384) = 1409024$$

$$HL = 2B00H$$

$$HL \times 80H = (2B00)_H \times (80)_H = 1409024 \text{ (Check)}$$

To accomplish the data manipulations required by FIR filters, it is convenient to define an FIFO memory file. The FIFO routine accepts a sample from the accumulator and stores it at the top of a table shifting all samples in the table one location down. The last sample into the table when FIFO is called is dumped into a garbage collecting location. The operation of the FIFO is illustrated in the Figure A-3.

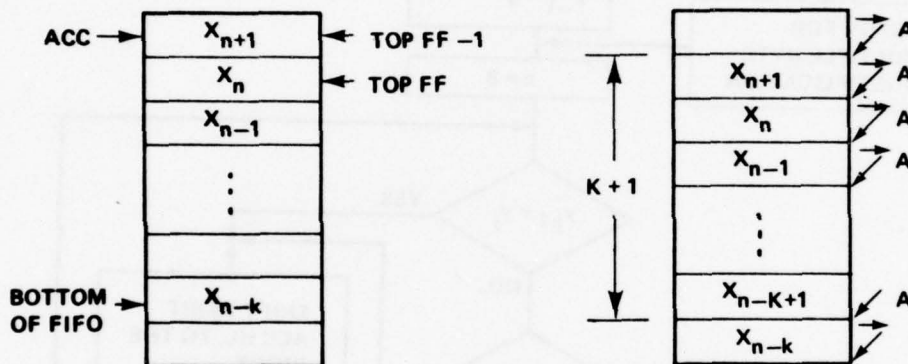


Figure A-3. FIFO operation.

The operation is best understood by referring to the source listing given in Appendix B. It is sufficient to say that to move each sample to the next lower position, it is first moved from memory into the accumulator and from there it is moved to the next location. There are two pointers HL and DE. HL points to the sample and DE points to the next location.

The IIR filter may be described by

$$y_n = \sum_{k=0}^z a_k x_{m-k} - \sum_{k=1}^z b_k y_{n-k} \quad (A-2)$$

where a_k and b_k are coefficients and x_n are samples.

To evaluate the preceding expression, it is expanded as

$$y_n = a_0 x_n + a_1 x_{n-1} + a_2 x_{n-2} - b_1 y_{n-1} - b_2 y_{n-2} \quad (A-3)$$

where a_0 , a_1 , a_2 , b_1 , and b_2 are stored in ROM or RAM as 16-bit two-complement numbers. The results y_n are also 16-bit numbers. x_n are 8-bit two-complement numbers. It is seen that both 16- by 16-bit and 16- by 8-bit multiplication is required. Also, care must be taken when adding the elements. Scaling must be taken into account because the results of 16- by 8-bit and 16- by 16-bit multiplications are added. It is assumed that the coefficients are scaled such that the elements can be directly summed.

To store x_n , x_{n-1} , and x_{n-2} three locations called $XN0$, $XN1$, and $XN2$ are used. When a new sample is given, then the sample in $XN0$ moves to $XN1$ and $XN1$ to $XN2$ while the new sample is stored in $XN0$. The third sample x_{n-3} is dumped. The IIR routine evaluates the expression according to the flowchart given in Figure A-4.

On entry to the IIR after initialization by calling $IIR1$, BC must contain y_{n-2} and HL , y_{n-1} . This condition is true when the IIR routine returns to the calling program. Therefore, care must be taken not to destroy these registers.

1. PROCESSING TIME

The processing time of each routine is given in terms of clock cycles. For the Intel 8080A standard package, a typical clock cycle is 500 nsec. ($K = K' + 1$) where K' = order of filter.

| <u>Routine</u> | <u>Clock Cycles</u> |
|----------------|--|
| MULT | MIN = 928 MAX = 1143 |
| FIFO | $88 + 42 K$ |
| FIR0 | $171 + 195 K + \text{MULT} \times K$ where $\text{MULT} \approx 1140$ |
| FIR1 | $150 + 170 K + \text{MULT} \times K$ |
| IIR0 | $502 + 2 \times \text{MULT} \times 16 + 3 \times \text{MULT}$ where $\text{MULT} \approx 2300$, $\text{MULT} \approx 1140$ |
| IIR1 | $427 + 2 \times \text{MULT} \times 16 + 3 \times \text{MULT}$ |
| FIR W/AMD 9511 | $171 + 388 K$ |
| W/O DMA | |

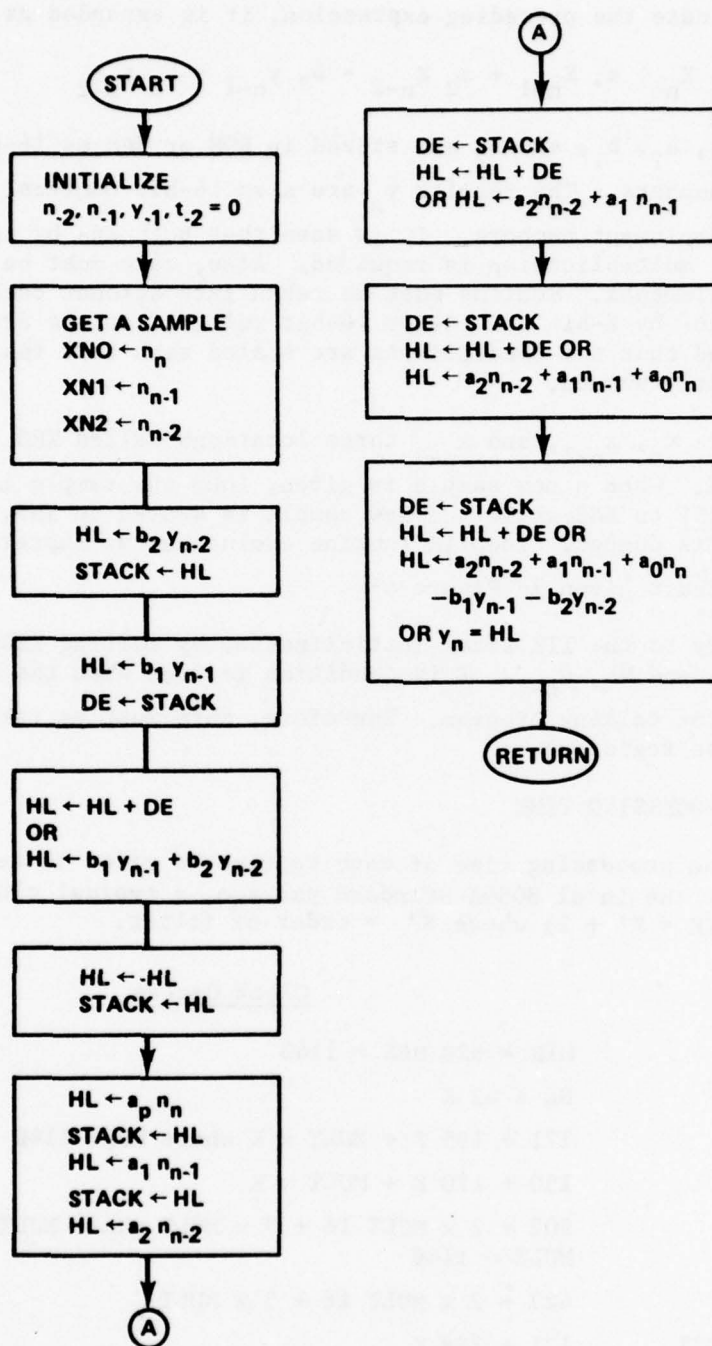


Figure A-4. IIR filter algorithm.

| <u>Routine</u> | <u>Clock Cycles</u> |
|----------------|--|
| FIR W/AMD 9511 | AM9511 requires 92 clk cycle multiply + 101 cycles load |
| W/DMA | 400 + 345 K + FIFO |
| IIR W/AMD9511 | 1238 cycles |
| W/O DMA | (Total) |

2. FIR, IIR FILTER TIMING

The following are the times in cycles required to process each sample for K^{th} order FIR and IIR filters.

a. FIR Filter

$$T = 55 + \text{FIFO} + (135 + \text{MULT}) K \quad (\text{A-4})$$

where FIFO is a software first-in first-out routine. ($\text{FIFO} = 88 + 42K$). MULT is the multiplication time. The 8-bit by 16-bit multiplication time depends on whether it is implemented in software or hardware. The following table gives the multiplication time in cycles for the configuration listed.

| <u>Configuration</u> | <u>MULT Cycles</u> |
|--|--------------------|
| Software 8- by 16-bit | 1140 average |
| Memory mapped hardware with hardware multiplication of (11 cycles or 5.5 μsec) | 58 |
| 9511 APU Memory mapped-no interrupt | 172 |

b. IIR Filter

$$T = 82 + [761 + 5 * \text{MULT } 16] \quad (\text{A-5})$$

where MULT 16 is a 16- by 16-bit multiplication

| <u>Configuration</u> | <u>Cycles</u> |
|--------------------------------|---------------|
| Software (16- \times 16-bit) | 2300 |
| Hardware memory mapped | 58 |
| APU memory mapped-no interrupt | 172 |

3. 16- × 16-Bit Multiplication Hardware Multiplication Alternatives

The purpose of this discussion is to outline briefly the hardware requirements of a memory mapped 16- × 16-bit hardware multiplication scheme. In addition, the advantages of memory mapped versus isolated I/O are explained by comparing the software necessary for moving data to and from the multiplication unit for each configuration. Hence, the software required for the operation $HL = HL * BC$ for each configuration are examined first.

a. Isolated I/O

An isolated I/O configuration is considered where data are sent to and received from an I/O device through the accumulator. Figure A-5 shows a block diagram of a 16- by 16-bit hardware multiplication unit. The I/O ports XL, XH, YK, and YH can be either isolated I/O ports or memory locations (memory mapped I/O). The necessary software and the corresponding cycles per instruction required to perform the operation $HL \leftarrow HL * BC$ are given in Figure A-5.

Cycles/Instruction

| | | | |
|----|-----|-----|-----------------------|
| 5 | MOV | A,C | ; |
| 10 | OUT | XL | ; XL = C |
| 5 | MOV | A,B | ; |
| 10 | OUT | XH | ; |
| 5 | MOV | A,L | ; XL = B |
| 10 | OUT | YL | ; |
| 5 | MOV | A,H | ; YL = L |
| 10 | OUT | YH | ; |
| 10 | IN | YL | ; YL = H |
| 5 | MOV | L,A | ; Y = Y * X + HL * BC |
| 10 | IN | YH | ; HL = Y |
| 5 | MOV | H,A | ; HL = HL * BC |

In the preceding routine, XL is the address of the lower 8-bit latch of X and XH is the address of the higher 8-bit latch of X. The same applies to YL and YH. Assuming that the hardware multiplier has a multiplication time of less than eight cycles (this is the time in cycles, between which YH is loaded with H by the instruction OUT YH and when Y_L must be put on the data bus during the instruction IN YL), the program requires 90 cycles of execution. In the light of the preceding discussion, memory mapped I/O is examined next.

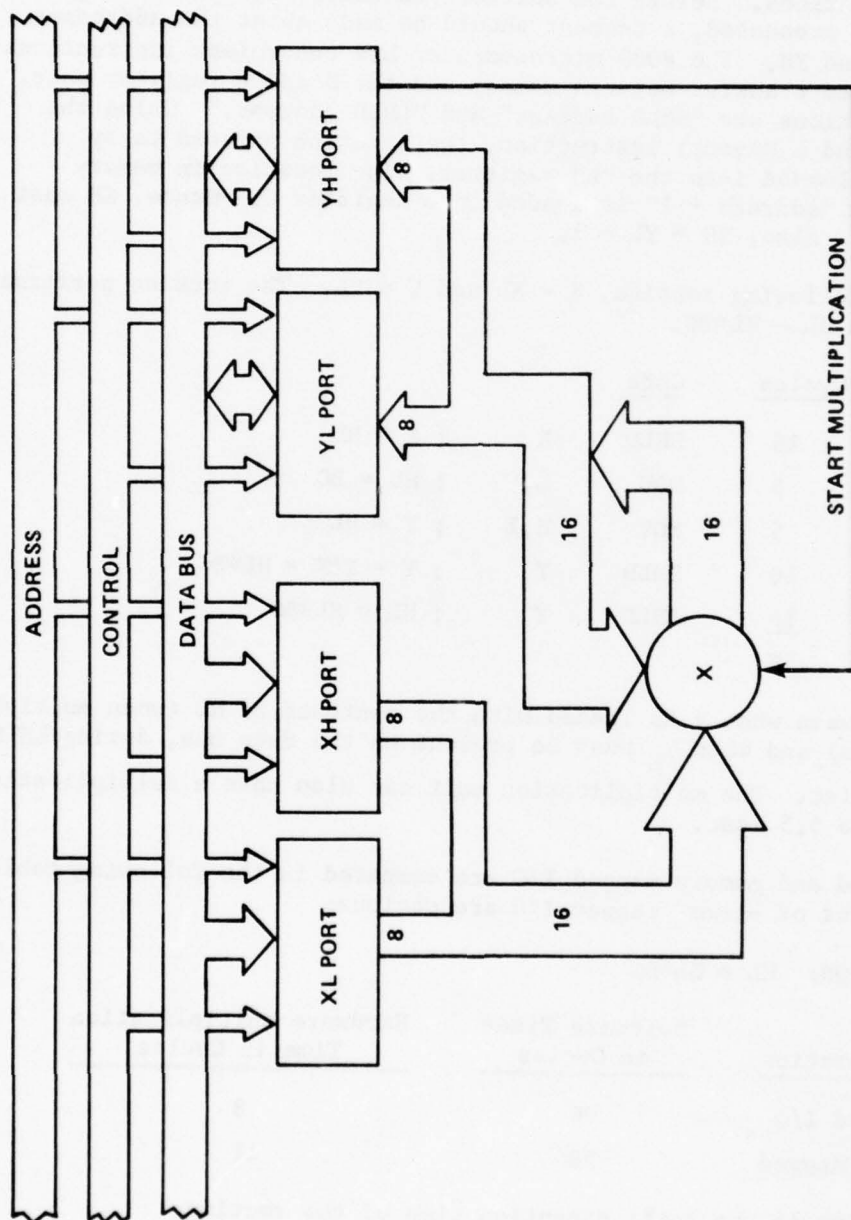


Figure A-5. I/O configuration for isolated or memory mapped hardware multiplication.

b. Memory Mapped I/O

In this case XL, XH, YL, and YH are actually locations in memory. In storing data to and from these locations, they are treated as memory locations. Before the software necessary for performing $HL = HL * BC$ is presented, a comment should be made about the addresses XL, XH, YL, and YH. The 8080 microcomputer has convenient instructions for 16-bit data transfer between memory and the H and L register pair. These instructions are "SHLD address" and "LHLD address." Using the LHLD (Load Hand L Direct) instruction, the location pointed to by "address" is loaded into the "L" register. The location in memory pointed to by "address + 1" is loaded into Register H. Hence, XH must equal $XL + 1$. Also, $YH = YL + 1$.

In the following routine, $X = XL$ and $Y = YL$. The routine performs the operation $HL \leftarrow HL * BC$.

| <u>Cycles</u> | <u>Code</u> | | |
|---------------|-------------|-----|-----------------------|
| 16 | SHLD | X | ; X = HL |
| 5 | MOV | L,C | ; HL = BC |
| 5 | MOV | H,B | ; Y = HL |
| 16 | SHLD | Y | ; Y = Y * X = HL * BC |
| <u>16</u> | LHLD | Y | ; HL = HL * BC |
| 58 | | | |

The time between when Y is loaded with the contents of HL (when multiplication starts) and when Y_L must be present on the data bus, during LHLD Y, is 11 cycles. The multiplication unit can also have a multiplication time of up to $5.5 \mu\text{sec}$.

Isolated and memory mapped I/O are compared in the following table. The advantages of memory mapped I/O are obvious:

OPERATION: $HL = HL * BC$

| <u>Configuration</u> | <u>Software Time* in Cycles</u> | <u>Hardware Multiplication Time in Cycles</u> |
|----------------------|-------------------------------------|---|
| Isolated I/O | 90 | 8 |
| Memory Mapped | 58 | 11 |

*Software time is the total execution time of the routine.

c. Hardware Implementation for Memory Mapped I/O

Figure A-6 presents a basic circuit necessary for storing the contents of the H and L registers into the latches (or shift registers) X_L and X_H using the "SALD X" instruction. The address X is actually the address of X_L and $X + 1$ is the address of X_H . For complete grouping of the hardware requirements of output and input operations, reference is made to pages 3-8 and 3-9 of the INTEL 8080 Microcomputer Users Manual for information of memory mapped I/O, and to pages 2-16 and 2-17 for a complete description of the cycles necessary for the execution of the SHLD and LHLD instructions.

Figure A-7 shows the circuit for input and output to locations Y_L and Y_H . In these circuits, the address X is defined as $A_{15} = 1$, $A_7 = 1$, $A_0 = 0$. The rest of the address bits are "don't cares" for $X_H = X + 1$; $A_{15} = 1$, $A_7 = 1$, and $A_0 = 1$.

The address of Y is defined as $A_{15} = 1$, $A_7 = 0$, $A_0 = 0$. The remaining address lines are "don't cares" (assuming that no other memory mapped I/O devices are present).

4. MEMORY MAPPED VERSUS ISOLATED I/O MULTIPLICATION USING THE Am 9511 APU

a. Introduction

The following is a comparison between memory mapped versus isolated I/O configurations of the AM 9511 APU in performing the following operations:

- 1) Two-complement 8- by 16-bit multiplication. That is, $HL = DE * A$.
- 2) Two-complement 16- by 16-bit multiplication. That is, $HL = HL * BC$.

b. Hardware Configuration:

Figure A-8 shows the hardware configuration of a memory mapped APU unit. Figure A-9 shows the configuration for an isolated I/O configuration.

c. Memory Mapped I/O Software, Operation $HL = B * HL$

The 8-bit two-complement number in A is multiplied by the 16-bit two-complement number in HL. The result is placed in HL.

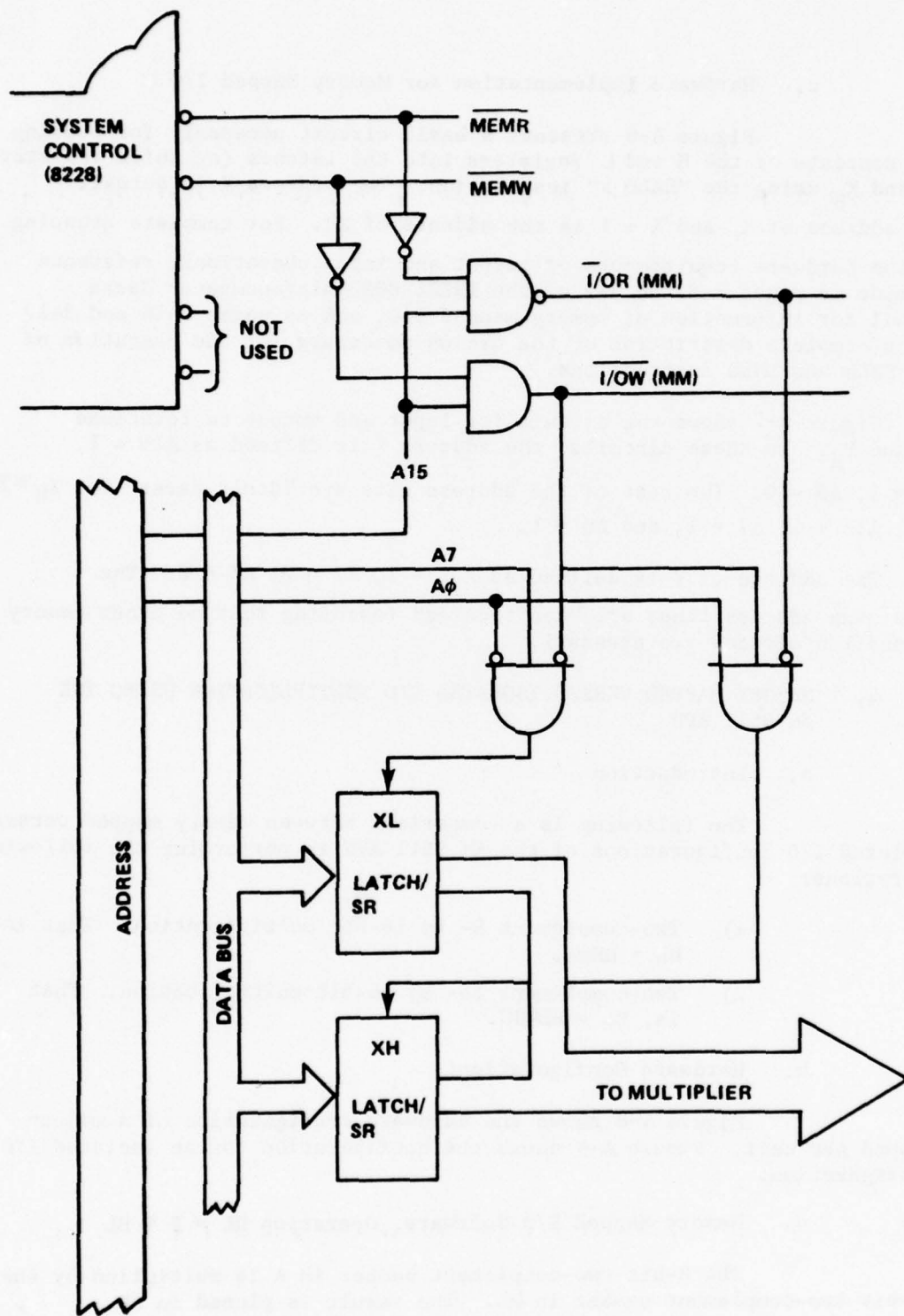


Figure A-6. Memory mapped hardware configuration for latching H and L from the data bus into the XL and XH latches.

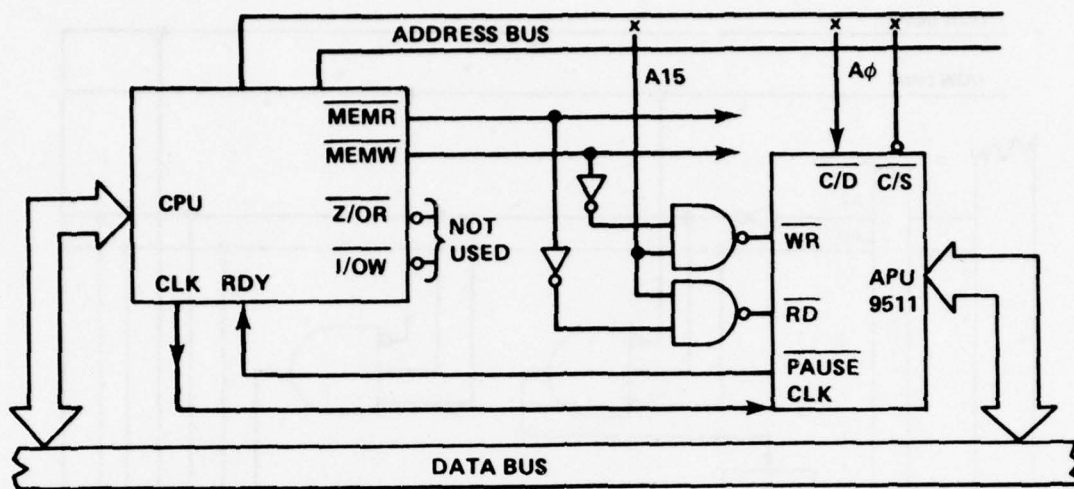


Figure A-8. Memory mapped APU.

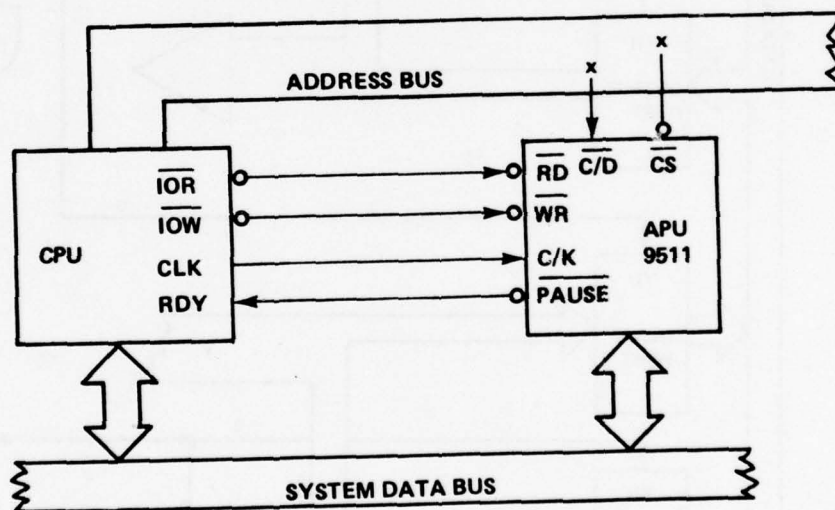


Figure A-9. Isolated I/O APU.

Cycles

| | | |
|--------|--------------|------------------------------|
| 10 | LXI D, APUAD | ; LOAD DE WITH APU ADDRESSES |
| 4 | XCHG | ; DE HL or HL = APUAD |
| 7 | MOV M, E | ; |
| 7 | MOV M,D | ; TOS = DE |
| 7 | MOV M,B | ; TOS = B, NOX = DE |
| 7 | MVI M,0 | ; |
| 5 | INX H | ; POINT TO COMMAND ADDRESS |
| 7 (96) | MVI M, SMUL | ; STORE MULTIPLY COMMAND |
| 5 | DCX H | ; POINT BACK TO DATA ADDRESS |
| 7 | MOV E,M | ; DE = DE*B |
| 7 | MOV D,M | ; |
| 4 | XCHG | ; HL = HL*B |

Total number of cycles = 169 (77 program, 92 MULT). When APUAD + 1 is put in the address bus, total number of cycles = 164 (72 program, 92 MULT). This method has less code and also is 5 cycles faster than method No. 1. APUAD, the address that sets CID low, and APUCM, the address that sets CID high, cannot be consecutive.

d. Isolated I/O Software Operation HL = HL*B

Cycles

| | | |
|---------|-------------|------------------------------|
| 5 | MOVE A,B | ; MOVE B into A |
| 10 | OUT APUAT | ; |
| 4 | XRA A | ; |
| 10 | OUT APUDAT | ; Clear A |
| 5 | MOV A,L | ; TOS = HL, NOS = B (16-bit) |
| 10 | OUT APUDAT | ; |
| 7 | MVI A, SMUL | ; MOVE MULT COMMAND INTO A |
| 10 (92) | OUT APUCM | ; SEND IT TO APU, CID = HIGH |
| 10 | IN APUDAT | ; MOVE TOS TO HL |
| 5 | MOV H,A | ; REGISTERS C/D = LOW |
| 10 | IN APUDAT | ; |
| 5 | MOV L,A | ; HL = HL*B |

Total number of cycles = 190 (106 program, 92 MULT).

Operation HL = HL*BC

The software is the same as for Operation HL = HL*B except that "XRA A" which was used to clear the accumulator is replaced by "MOV A,C" so that TOS = BC. Hence, one cycle is added to the previous program. Thus, for HL = HL*BC, total cycle time equals 199 (107 program, 92 MULT). The CID line must go high indicating that the data on the data bus are a command (multiplication in this case). When APUAD is put on the address bus, CID must be low.

Operation HL = HL*BC

The two-complement 16-bit numbers in HL and BC are multiplied. The result is placed in HL in the Memory Mapped Configuration.

| <u>Cycles</u> | <u>Method No. 1</u> | |
|---------------|---------------------|-------------------------------|
| 10 | LXI D, APUAD | ; LOAD DE WITH APU ADDRESS |
| 4 | XCHG | ; DE HL |
| 7 | MOV M,E | ; MOVE DE (OLD HL) INTO APU |
| 7 | MOV M,D | ; STACK |
| 7 | MOV M,C | ; MOVE BC INTO APU STACK |
| 7 | MOV M,B | ; BC = TOS, DE = NOX |
| 5 | INX H | ; CID = HIGH |
| 7 | MVI M,SMUL | ; SEND MULTIPLICATION COMMAND |
| 5 | DCX H | ; CID = LOW |
| 7 | MOV E,M | ; |
| 7 | MOV D,M | ; |
| 4 | XCHG | ; DE HL or HL = HL*BC |

Total Number of Cycles = 169 (77 program, 92 MULT).

| <u>Cycles</u> | <u>Method No. 2</u> | |
|---------------|---------------------|---------------------------|
| 10 | LXI SP,APUDAT | ; LOAD STACK POINTER WITH |
| 11 | PUSH H | ; APU DATA ADDRESS |
| 11 | PUSH B | ; HL = TOS |
| 2 | MVI A,SMUL | ; BC = TOS, HL = NOS |
| 13 | STA APUCM | ; TOS = NOS*TOS = HL*BC |
| 10 | POP H | ; HL = TOS REVERSED |
| 5 | MOV A,L | ; L H |
| 5 | MOV L,H | ; |
| 5 | MOV H,A | ; HL = HL*BC |

4. SUMMARY

The results obtained for each operation using memory mapped I/O, or isolated I/O are tabulated with the cycle time and necessary memory storage for each method, as follows:

| <u>Operation</u> | <u>Configuration</u> | <u>No. of Bytes Storage Required</u> | <u>Cycles</u> |
|------------------|--------------------------------|--|---------------|
| HL = HL*B | Memory Mapped, Method No. 1 | 16 | 169 |
| HL = HL*B | Memory Mapped, Method No. 2 | 16 | 170 |
| HL = HL*B | Isolated I/O | 22 | 198 |
| HL = HL*BC | Memory Mapped, Method No. 1 | 15 | 169 |
| HL = HL*BC | Memory Mapped, Method No. 2 | 14 | 164 |
| HL = HL*BC | Isolated I/O | 22 | 199 |

Because it takes $11 + 10 = 21$ (RST + RET) cycles just to service an interrupt without performing any operation, using the multiplication feature of the APV with 92 cycles execution time with an interrupt is unreasonable.

Appendix B. 8080A MICROPROCESSOR BENCHMARK PROGRAM LISTINGS

FIR DIGITAL FILTER


```

; *****
;
; THE FOLLOWING PROGRAM ILLUSTRATES HOW RESULTS
; ARE OBTAINED FROM THE FIR FILTER
; SAMCNT INITIALLY IS THE NUMBER OF SAMPLES
; SCNT IS WHERE THE SAMPLE COUNT IS STORED
; K IS THE NUMBER OF ELEMENTS SUMMED
; *****
SCNT EQU 0380H
SAMCNT EQU 10
K EQU 7
ORG 0200H
LXI SP, 0200H; INITIALIZE STACK POINTER
LXI H, XTABL; INITIALIZE POINTER
SHLD XPNTR; STORE X(N) TABLE ADDR. IN POINTER
LXI H, YTABL; INITIALIZE POINTER
SHLD YPNTR; STORE Y(N) TABLE ADDR. IN POINTER
MVI A, SAMCNT-1; INITIALIZE SAMPLE COUNT
STA SCNT; SAVE COUNT IN LOC. SCNT
CALL FIR0; INITIALIZE
FILTER: CALL FIR1
        LDA SCNT; CHECK SAMPLE COUNT
        DCR A;
        STA SCNT; SAVE SCNT; SAMPLE COUNT
        INZ FILTER
        JAP 3400H; JUMP TO MONITOR IF THROUGH
; *****
;
; T A B L E S
; *****
ORG 0300H
; COEFFICIENT TABLE (HCK)
; COEF IS THE PAGE WHERE THE COEFF. ARE STORED
COEF EQU 03H
COEFF: DW 0FF45H
        DW 0FF7DH
        DW 0FF76H
        DW 0798H
        DW 0FF76H
        DW 0FF7DH
        DW 0FF45H
        DW 000000
; FIFO STORAGE
COEFF: DS 15
ENDOFF: DS 1
; X TABLE WHERE X SAMPLES ARE STORED
XPNTR: DS 2
XTABL: DB 100
        DB 0
        DB 0
        DB 0
        DB 0
        DB 0
        DB 0
        DB 0
        DB 0
        DB 0
; Y TABLE WHERE Y SAMPLES ARE STORED
YPNTR: DS 2
YTABL: DS 20
        ORG 3400H

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*****
*
*      F I F O   R O U T I N E
*
*****
ENDFF EQU      TOPFF+K-1
FIFO: STA      TOPFF-1 ; TOPFF IS THE ADDRESS OF THE FIFO
      LXT      H,ENDFF ; ENDFF IS THE ADDRESS OF THE BOTTOM
      LXT      D,ENDFF+1 ; OF THE FIFO.
      MVI      C,K+1 ; K IS NUMBER OF ELEMENTS
      MOV      A,H ; EACH LOCATION IS MOVED DOWN
      MOVDOWN: STAX D ; TO THE NEXT LOCATION STARTING FROM
      DCR      C ; THE BOTTOM OF THE FIFO. HENCE
      RZ       ; X(N) IS MOVED TO THE TOP AND
      DCX      H ; X(N-K-1) IS DUMPED FROM THE
      DCX      D ; BOTTOM
      JMP      MOVDOWN
*****
*
*      M U L T I P L Y   R O U T I N E
*
*****
THE FOLLOWING PROGRAM MULTIPLIES THE 8 BIT TWO'S COMPLEMENT
NUMBER IN ACC BY THE 16 BIT TWO'S COMPLEMENT NUMBER
IN THE REGISTER PAIR DE AND PLACES THE RESULT IN THE
REGISTER PAIR HL IN TWO'S COMPLEMENT. REGISTERS BC
ARE SAVED

MULT:  LXT      H,0000H ; CLEAR H AND L
      ORA      A ; CLEAR CARRY Y(-1)=0
      RZ       ; RETURN IF MULTIPLYER IS ZERO. HL=0000
      PUSH     H ; SAVE HC PAIR ON STACK
MULT16: MVI     C,8 ; INITIALIZE COUNT
      JMP      ENTER ; START MULTIPLICATION ENTRY POINT
      ; FOR MULTIBYTE MULTIPLICATION.
      ADDI: DAD     D ; ADDITION: HL=HL+DE
      JMP      COUNT ; CHECK COUNT
      SUBTR: MJB     A,L ; THIS IS TO SUBTRACT DE FROM HL
      SUB      E ; HL=HL-DE
      MOV      L,A
      MOV      A,H
      SBB      D,H ; SUBTRACT D FROM H WITH BORROW
      MOV      H,A ; GENERATED FROM L-E.
COUNT: DCR      C ; CHECK COUNT
      JNZ      ROTATE ; IF NOT THROUGH THEN ROTATE HL TO THE RIGHT
      POP      PSW ; RESTORE ACC AND CARRY
      POP      B ; RESTORE BC REGISTERS
      RET      ; RETURN TO CALLING PROGRAM
      ROTATE: MOV     A,H ; THIS IS TO ROTATE HL TO THE RIGHT
      ORA      A ; CHECK H TO SEE IF HL IS NEG.
      JP      POSITV ; IF SO THEN INSERT A ONE IN MSB WHEN
      POSITV: STC     ; ROTATING, THAT IS SET CARRY ON NEG. H
      RAR      ; ROTATE H TO THE RIGHT THROUGH CARRY
      MOV      H,A
      MOV      A,L
      RAR      ; ROTATE L THROUGH CARRY
      POP      PSW ; RESTORE ACC AND CARRY
      ENTER: JC      CARRY ; Y(J-1)=1 IF CARRY
      RAR      ; CARRY=Y(J)
      PUSH     PSW ; SAVE ACC AND CARRY ON STACK
      JC      SUBTR ; SUBTRACT DE FROM HL IF Y(J)=1 AND Y(J-1)=0
      JMP      COUNT ; ROTATE IF Y(J)=Y(J-1)=0
      CARRY: RAR      ; Y(J-1)=1
      PUSH     PSW ; SAVE ACC AND CARRY,Y(J), ON STACK
      JC      COUNT ; ROTATE IF Y(J)=Y(J-1)=1
      JMP      ADDI ; ADD DE TO HL IF Y(J)=0, Y(J-1)=1

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*****
* THIS ROUTINE MULTIPLIES TWO 16-BIT *
* TWO'S COMPLEMENT NUMBERS IN BC AND DE *
* AND PLACES THE RESULT IN HL. *
*****
MULT16: MOV     A,C
        CALL    MULT
        MOV     A,B
        CALL    MUL16
        RET

; OUTPUT: Y(N) O U T P U T *****
XCHG    YPNTN ; NOW DE CONTAINS Y(N)
LHLD    YPNTN ; LOAD HL WITH TABLE POINTER
MOV     H,E    ; MOVE LEAST SIG BYTE OF Y(N) INTO
INX     H,D    ; TABLE. POINT TO MOST SIG. BYTE
MOV     H,D    ; STORE MOST SIG. BYTE INTO MEMORY
INX     H
SHLD    YPNTN ; STORE TABLE POINTER IN YTABL IN MEM.
XCHG    RET    ; HL NOW CONTAINS Y(N)

; ATOD: A T O D *****
LHLD    XPNTN ; LOAD HL WITH X(N) TABLE POINTER
MOV     A,H    ; ACC=X(N)
INX     A      ; POINT TO X(N+1)
SHLD    XPNTN ; SAVE POINTER
RET

*****
* F I R D I G I T A L *
* F I L T E R *
*****
* THE COEFF. ARE STORED IN A TABLE *
* CALLED COEFF AS 16-BIT TWO'S COMPLEMENT *
* NUMBERS. X(N-KK) ARE STORED IN LOCATION *
* FIFO AS 8-BIT TWO'S COMPLEMENT NUMBERS *
* CALL FIR0 FOR INITIALIZATION. *
* CALL FIR1 FOR SUBSEQUENT RESULTS *
*****
FIR0:   LXI     H,TOEFF ; HL POINTS TO THE FIFO
        MVI     C,K    ; K IS THE NUMBER OF ADDITIONS IN SUM
        XRA     A      ; CLEAR ACC. THE FOLLOWING INITIALIZES
ZERO:   MOV     M,A    ; THE FIFO SO THAT X(N) FOR
        INX     H      ; N-1 EQUAL TO ZERO
        DCR     C      ; CHECK COUNT
        JNZ     ZERO   ; PUT ZEROS UNTIL END OF FIFO
        CALL    ATOD   ; A=X(N)
        CALL    FIFO   ; PUT X(N) ON TOP OF FIFO AND
        LXI     H,0000H ; DUMP X(N-K-1). CLEAR SUM
        MVI     B,0    ; B CONTAINS LOWER ADDRESS OF COEFF.
        MVI     C,K    ; K IS THE NUMBER OF SAMPLES SUMMED
        LXI     H,TOEFF ; DE POINTS TO THE TOP OF FIFO
        PUSH    D      ; SAVE DE ON STACK
        POP     D      ; RESTORE DE FROM STACK
        LDAX    D      ; ACC=X(N-KK)
        INX     D      ; POINT TO X(N-KK+1)
        PUSH    D      ; SAVE SAMPLE ADDRESS ON STACK
        PUSH    D      ; SAVE INTERMEDIATE SUM ON STACK
        MOV     H,B    ; MOVE COEFF COUNT INTO REG. L
        MVI     H,COEF ; HL NOW POINTS TO COEFF'S H(KK)
        MOV     D,H    ; MOVE H(KK) INTO DE REGISTER PAIR
        INR     L      ; POINT TO MOST SIG BYTE OF COEFF.
        MOV     D,M    ; MOVE IT INTO D
        INR     L      ; POINT TO NEXT COEFF.
        MOV     B,L    ; SAVE COEFF. COUNT IN REG. B
        MOV     B,L    ; MULT MULTIPLIES DE BY ACC PUTS
        CALL    MULT   ; RESULT IN HL, HL=ACC*DE
        LXI     H,0    ; HL=X(N-KK)*H(KK)
        POP     D      ; PUT INTERMEDIATE SUM FROM STACK
        DAD     D      ; INTO DE REGISTERS AND ADD TO HL
        DCR     C      ; HL=SUM+X(N-KK)*H(KK). DECREMENT COUNT
        JNZ     START  ; CHECK IF K ELEMENTS SUMMED
        POP     D      ; RETURN ADDRESS NOW ON STACK
        CALL    OUTPUT ; STORE Y(N) IN TABLE
        RET
END

```

IIR DIGITAL FILTER

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*****
THE FOLLOWING PROGRAM CALCULATES Y(N), THE RESPONSE OF A
K-TH ORDER DIGITAL FILTER TO AN INPUT X(N). THE FILTER
IS IMPLEMENTED IN SECTIONS. EACH SECTION IS A SECOND
ORDER IIR FILTER THAT CALCULATES THE FOLLOWING:
Y(N)=A0*X(N)+A1*X(N-1)+A2*X(N-2)-B1*Y(N-1)-B2*Y(N-2)
X(N), X(N-1), ..., X(N-1), ..., A0, A1, A2, B1, B2, ARE ALL
16-BIT TWO'S COMPLEMENT NUMBERS.
SINCE EACH SECTION NEEDS ITS OWN COEFFICIENTS AND
PREVIOUS VALUES, THE PROGRAM HAS TWO TABLES, THE COEFF.
TABLE AND THE XY TABLE. IN THE LATTER, THE PREVIOUS
VALUES X(N-1), X(N-2), ... ARE STORED. THE TABLES ARE
DIVIDED INTO SECTIONS, EACH SECTION CONTAINING COEFF.'S
AND PREVIOUS VALUES FOR A PARTICULAR FILTER SECTION.
THE CONTENTS OF THE XY TABLE ARE MODIFIED AT THE END
OF EACH SECTION CALCULATION, THAT IS, X(N) BECOMES X(N-1)
AND X(N-1) BECOMES X(N-2) ETC. THE XY TABLE IS REFERRED
TO AS XYTAB. A POINTER CALLED XYPTR POINTS TO THE APPROPRIATE
SECTION ADDRESS IN THE TABLE AT THE BEGINNING OF
EACH IIR FILTER SECTION CALCULATION. EACH SECTION IN THE
TABLE CONTAINS THE FOLLOWING PREVIOUS CONDITIONS IN THE
ORDER INDICATED: Y(N-2), Y(N-1), X(N-2), X(N-1).
THE COEFFICIENTS FOR EACH SECTION ARE STORED IN THE
FOLLOWING ORDER: B2, B1, A2, A1, A0.
A SINGLE ROUTINE IS USED TO CALCULATE THE IIR RESPONSE
TO AN OUTPUT FROM A PREVIOUS SECTION. THIS ROUTINE
ASSUMES THAT THE PREVIOUS VALUES AND COEFF.'S FOR THAT
SECTION HAVE BEEN MOVED FROM THE TABLES TO THE FOLLOWING
LOCATIONS: Y(N-2) INTO YNM2, Y(N-1) INTO YNM1, X(N-2)
INTO XNM2, X(N-1) INTO XNM1 AND X(N) INTO XNM0 AND THE
COEFF. B2 INTO LOC. B2, COEFF. B1 INTO LOC B1, ETC.
THE OUTPUT FROM EACH SECTION IS STORED IN LOCATION XNM0
TO BE USED AS INPUT TO THE NEXT SECTION.
THE FINAL OUTPUT IS OBTAINED IN THE HL REGISTER PAIR,
*****
IIR:   LXI     H,XYTAB ; INITIALIZE XY TABLE POINTER,POINTING
      SHLD   XYPTR ; TO PREVIOUS VALUES: X(N-2),...
      LXI     H,CFTBL ; INITIALIZE COEFFICIENT TABLE POINTER
      SHLD   CFPTR
      LHL    XN      ; HL=X(N) ASSUMING X(N) IN LOC. XN, (A/D MM)
      MVI    A,KD2   ; INITIALIZE SECTION COUNT
SECTN: STA     SECT   ;KD2=K/2 IS NUMBER OF SECTIONS, SAVE COUNT
      SHLD   XNM0    ; STORE X(N) INTO LOC. XNM0
;
;
;
PREV MOVES THE PREVIOUS VALUES Y(N-2),Y(N-1),... INTO
LOCATIONS YNM2,YNM1,... USED BY IIRS TO CALCULATE Y(N)
;
;
PREV:  LHL    XYPTR  ; LOAD HL WITH XYPTR WHICH POINTS TO PREVIOUS
      SPHL                     ;VALUE SECTION IN XYTAB. MOVE TO STACK POINTER
      MOV     A,L
      ADI     8
      JNC    NEXT
      INR     H
NEXT:  MOV     L,A
      SHLD   XYPTR
      ; HL=HL+8
      ; MODIFY POINTER TO POINT TO NEXT SECTION
      ; XYPTR=XYPTR+8
      POP     H
      SHLD   YNM2
      POP     H
      SHLD   YNM1
      POP     H
      ; STACK POINTS TO Y(N-2) SO POP H
      ; LOADS Y(N-2) INTO H AND L
      ; POPPING AGAIN LOADS Y(N-1) INTO HL
      ; STORE Y(N-2),Y(N-1),...AS THEY ARE POPPED
      ; INTO LOCATIONS YNM2,YNM1,XNM2,XNM1.
      SHLD   XNM2
      POP     H
      SHLD   XNM1
;

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*
* CPMOV MOVES THE COEFFICIENTS FOR THE SECTION TO BE
* CALCULATED FROM CFTBL TO LOCATIONS B2,B1,...
*
CPMOV:  LHL  CFPTR  ; MOVE CFPTR WHICH POINTS TO COEFFICIENTS
        SPHL      ; FOR SECTION TO BE CALCULATED TO
        MOV  L,A   ; STACK POINTER
        ADI  10    ; CALCULATE HL=HL+10
        JNC  NEXT2 ; INCREMENT H IF CARRY
NEXT2:  INC  H      ;
        MOV  A,L   ; HL=HL+10
        SHLD CFPTR ; MODIFY POINTER TO POINT TO NEXT SECTION
                ; CFPTR=CFPTR+10
        POP  H      ; MOVE B2,B1,... INTO LOCATIONS B2,B1,...
        SHLD B2     ; BY POPPING B2,B1,... INTO HL AND THEN
        POP  H      ; STORING THEM INTO LOCATIONS B2,B1,...
        SHLD B1     ; USED TO CALCULATE IIR RESPONSE.
        POP  H      ;
        SHLD A2     ;
        POP  H      ;
        SHLD A1     ;
        POP  H      ;
        SHLD A0     ;
*
* THE FOLLOWING CALCULATES Y(N) FOR AN IIR SECTION
* ACCORDING TO THE FOLLOWING:
*  $Y(N) = A0 \cdot X(N) + A1 \cdot X(N-1) + A2 \cdot X(N-2) - B1 \cdot Y(N-1) - B2 \cdot Y(N-2)$ 
* Y(N-2), Y(N-1), X(N-2), X(N-1), AND X(N) MUST BE IN LOCATIONS
* YNM2, YNM1, XNM2, XNM1, AND XNM0. THE COEFFICIENTS MUST BE
* IN LOCATIONS B2,B1,A2,A1,A0. Y(N) IS CALCULATED AND PUT
* IN THE H AND L REGISTERS, B2,B1,... ARE DESTROYED.
*
IIR:    LXI  SP, B2 ; STACK POINTS TO B2 WHICH CONTAINS COEF. B2
        POP  B      ; BC=B2
        LHL  YNM2   ; HL=Y(N-2)
        CALL MUL16  ; HL=HL*BC, HL=Y(N-2)*B2
        XCHG      ; DE=HL
        POP  B      ; BC=B1
        LHL  YNM1   ; HL=Y(N-1)
        CALL MUL16  ; HL=HL*BC, HL=Y(N-1)*B1
        XCHG      ; DE=HL
        DAD  D      ; HL=B1*Y(N-1)+B2*Y(N-2)
        XRA  A      ; CLEAR ACC.
        SUR  L,A    ; A=0-L
        MOV  L,A    ;
        MVI  A,0    ; CAREFUL NOT TO DESTROY CARRY
        SBB  H,A    ; HL=-HL
        MOV  H,A    ;
        XCHG      ; DE=-HL=-B1*Y(N-1)-B2*Y(N-2)
        POP  B      ; BC=A2
        LHL  XNM2   ; HL=X(N-2)
        CALL MUL16  ; HL=HL*BC, HL=X(N-2)*B2
        DAD  D      ; HL=A2*X(N-2)+Y(N-1)*B1+...
        XCHG      ; DE=HL
        POP  B      ; BC=A1
        LHL  XNM1   ; HL=X(N-1)
        CALL MUL16  ; HL=HL*BC, HL=X(N-1)*A1
        DAD  D      ; HL=A1*X(N-1)+...-B1*Y(N-1)-...
        POP  B      ; BC=A0
        LHL  XNM0   ; HL=X(N)
        CALL MUL16  ; HL=HL*BC, HL=A0*X(N)
        DAD  D      ; HL=Y(N)=A0*X(N)+A1*X(N-1)+...-B1*Y(N-1)-...

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* TRANS TRANSFERS Y(N), Y(N-1), X(N), X(N-1) TO THE XYTBL
* LOCATIONS OF THE SECTION JUST CALCULATED TO BE USED AS
* Y(N-1), Y(N-2), X(N-1), AND X(N-2) THE NEXT TIME AROUND.
*
TRANS: XCHG      ; DE=Y(N)
        LHLD     XYPTR ; MOVE XY TABLE POINTER WHICH POINTS TO
        SPHL     ; NEXT SECTION TO STACK.
        LHLD     XNMO  ; HL=X(N) IS PUSHED ON THE STACK.
        PUSH     H      ; HENCE IT BECOMES X(N-1) OF THE SECTION
        LHLD     XNM1  ; JUST EVALUATED. LIKEWISE X(N-1) IS
        PUSH     H      ; IS STORED INTO THE X(N-2) LOCATION OF
        PUSH     D      ; THE SECTION IN XYTBL. SO ARE
        LHLD     YNM1  ; Y(N) AND Y(N-1) THAT BECOME Y(N-1), Y(N-2)
        PUSH     H      ; THE NEXT TIME AROUND.
        XCHG     ; HL=DE=Y(N) WHICH IS X(N) FOR NEXT SECTION.
        LDA      SECNT ; LOAD ACC. WITH SECTION COUNT
        OCR      A      ; DECREMENT SECTION COUNT
        JNZ      SECTN  ; CHECK TO SEE IF LAST SECTION.
        ; EXIT WITH Y(N) IN H AND L REGISTER PAIR
END
/*

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```

*****
* THE FOLLOWING IS AN 8080 PROGRAM FOR DECIMATION-IN-TIME *
* RADIX 2, IN-PLACE FAST FOURIER TRANSFORM. *
* THE SAMPLES ARE STORED IN A TABLE CALLED XTABL. EACH SAMPLE *
* IS STORED AS A COMPLEX NUMBER WITH 16-BIT TWO'S COMPLEMENT *
* REAL AND IMAGINARY PARTS. *
* REFERENCE IS MADE TO THE FORTRAN DECIMATION-IN-TIME, RADIX 2, *
* IN-PLACE FFT ROUTINE BY COOPLY, LEWIS, AND WELCH (PAGE 367, *
* RABINEU AND GOLD'S "DIGITAL SIGNAL PROCESSING"). *
*****
* THE MAXIMUM NUMBER OF SAMPLES, N, IS NMAX=256. *
*****
* IN-PLACE BIT-REVERSAL SHUFFLING ROUTINE. *
* SUBROUTINE MOVE IS USED TO MOVE THE REAL AND IMAGINARY PART *
* OF THE COMPLEX VARIABLE ADDRESSED BY HL INTO THE LOCATION *
* ADDRESSED BY DE. *
*****
MOVE: MVI C,4 ; INITIALIZE COUNT IN C REGISTER
*****
MOVE1: MOV A,H ; MOVE FIRST BYTE OF REAL PART INTO
STAX D ; ACCUMULATOR AND FROM THERE STORE THEM
INX D ; INTO LOCATION ADDRESSED BY DE.
INX D ; INCREMENT HL AND DE.
DCR C ; DO FOR FOUR BYTES.
JNZ MOVE1 ; CHECK TO SEE IF FOUR BYTES MOVED.
RET
*****
* THE FOLLOWING DOES THE IN-PLACE BIT-REVERSED SHUFFLING. *
* REGISTER B CONTAINS THE BIT-REVERSED CODE OF THE COUNT PLACED *
* IN REGISTER E, N IS THE NUMBER OF SAMPLES WHICH IS PLACED *
* IN REGISTER D. *
*****
INPBR: LXI H,XTABL ; HL POINTS TO TABLE WITH SAMPLES X.
MVI D,N ; MOVE NUMBER OF SAMPLES, N, INTO REG. D.
XRA A ; CLEAR ACC.
MOV C,A ; CLEAR REG. E.
*****
MOV B,A ; E WILL CONTAIN COUNT AS WE MOVE
; DOWN THE XTABL CONTAINING SAMPLES.
; CLEAR B.
*****
SHFFL: SUB E ; B WILL CONTAIN BIT REVERSED NUMBER OF D.
JZ NUNEEED ; A=B-E. IF B>E THEN REVERSE POSITIONS.
JC NUNEEED ; IF B=E THEN NO NEED TO REVERSE.
; IF E>B THEN ALREADY REVERSED BEFORE.
REVERSE: PUSH D ; SAVE DE REGISTERS
PUSH H ; SAVE ADDRESS OF CURRENT SAMPLE ADDRESS
PUSH H ; SAVE TWO LEVELS DEEP ON STACK.
LXI D,TEMP ; LOAD DE WITH ADDR. OF TEMPORARY LOC.
CALL MOVE ; MOVE SAMPLE INTO TEMP LOCATION.
MVI H,0 ; SET HL=A
MOV L,A ;
DAD H ; HL=2*A
DAD H ; HL=4*A
DAD D ; HL=CURRENT SAMPLE ADDR. + 4*A.
PUSH H ; HL NOW CONTAINS ADDRESS OF LOC. TO BE
; SHUFFLED IN-PLACE. SAVE HL ON STACK
CALL MOVE ; MOVE SAMPLE IN LOC. ADDRESSED BY HL TO
; LOCATION IN DE (CURRENT SAMPLE)
POP H ; RESTORE ADDRESS OF CURRENT SAMPLE.
XCHG ; RESTORE DE REGISTERS.
CALL MOVE ; MOVE SAMPLE IN LOC. TEMP INTO
; LOCATION OBTAINED BY BIT-REVERSAL.
POP H ; RESTORE ADDRESS OF CURRENT SAMPLE.
POP H ; RESTORE DE REGISTERS.
NUNEEED: INR E ; INCREMENT COUNTER E TO POINT TO NEXT SAMPLE
CALL BITREV ; BIT-REVERSE E. RETURN WITH BIT-REVERSED
MOV B,A ; NUMBER IN ACC. PUT IT INTO B.
INX H ;
INX H ;
INX H ;
INX H ;
DCR D ; HL=HL+4. HL NOW POINTS TO NEXT SAMPLE IN XTABL.
JNZ SHFFL ; CHECK TO SEE IF N SAMPLES SHUFFLED.
; KEEP ON SHUFFLING.

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* THE FOLLOWING ROUTINE OBTAINS THE NEXT BIT-REVERSED NUMBER
* FROM THE PREVIOUS ONE IN THE B REGISTER. THE METHOD USED IS
* BASED ON THE FLOW-CHART ON PAGE 365 OF RABINEU AND GOLD'S
* "DIGITAL SIGNAL PROCESSING". ON EXIT THE BIT-REVERSED NUMBER
* IS IN THE ACCUMULATOR.
*
*
BITREV: MOV     A,B      ; MOVE PREVIOUS BIT-REVERSED NUMBER
        MVI     C,9-LN  ; INTO ACC, THE BIT-REVERSED NUMBER MUST BE
LR0TN:  DCR     C        ; NORMALIZED. LN=LOG(BASE TWO)(C N)
                                ; HENCE 8-LN ARE THE NUMBER OF TIMES THE
                                ; NUMBER MUST BE SHIFTED TO THE LEFT,
                                ; EXIT CONDITION,
                                ; ROTATE ACC. TO THE LEFT
        JZ      START
        RLC
START:  JMP     LR0TN    ; START BIT-REVERSAL PROCESS
        MVI     C,N/2
R0TX:  RAL
R0TX:  JC      SUBONE
R0TX:  MOV     A,C
R0TX:  XRA     B        ; A= BIT- REVERSED NUMBER.
R0TX:  DCI     9-LK     ; BEGIN DENORMALIZATION.
R0TN:  DCR     C
RR      ;
RR      ; RETURN
SUBONE: RRC           ; ROTATE ACC. RIGHT
        MOV     D,A    ; A TRICK TO PERFORM:
        MOV     A,C    ; X+(1-2-4-...-N/2) BY CALCULATING
        RRC          ; (1-2-4-...-N/2) AND PUTTING IT IN C
        XRA     C
        MOV     C,A
        MOV     D,A
        JMP     R0TX
*
* THIS PORTION IMPLEMENTS THE EQUIVALENT OF THE FOLLOWING
* FORTRAN CODE:
*
*      DO 20 I=1,M
*      LE=2**I
*      LE1=LE/2
*      U=(1.0,0.0)
*      W=CMPLX(COS(PI/LE1),SIN(PI/LE1))
*      DO 10 J=J,N,LE
*      DO 20 J=1,LE1
*      IP=I+LE1
*      10 A(I)=A(IP)+T
*      20 U=U*W
*
* STORAGE LOCATION LL CONTAINS 'L', REGISTERS D AND E CONTAIN
* 'J' AND 'I' RESPECTIVELY. LE1 IS KEPT IN REGISTER B AND
* LE IS KEPT IN REGISTER C.
* ALL COMPLEX VALUES HAVE 16-BIT TWO'S COMPLEMENT REAL AND
* IMAGINARY PARTS.

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CDE: MVI A,1 ; BEGIN DO LOOP WITH 'L'=1
      STA LL ; STORE 'L' IN LOCATION LL
      MOV C,A ; SAVE 'L' IN C TO CALCULATE LE LATER
POWER: MVI A,1 ; THIS PORTION CALCULATES
      ADD A ; A=2**L
      DCR C
      JNZ POWER ; THIS IS DONE BY SHIFTING A=1 TO
      MOV C,A ; THE RIGHT 'L' TIMES.
      RRC ; C=2**L=LE
      MOV B,A ; A=A/2=LE/2=LE1
      LXI H,ONE ; B=LE1
      SHLD UREAL ; LOAD HL WITH REAL 1.0
      SHLD UR ; STORE HL INTO UREAL
      SHLD ACCR ; ACCR=1.0
      LXI H,ZERO ; LOAD H WITH 0.0
      SHLD UIMAG ; UIMAG=0.0
      SHLD ACCI ; ACCI=0.0
      CALL WCALC ; U=(1.0,0.0), ACC=(1.0,0.0)
      MVI A,1 ; CALCULATE W = CMPLX(COS(PI/LE1), SIN(PI/LE1))
      MOV D,A ; INITIALIZE DO LOOP
      MOV E,A ; E='J'
      ADD B ; 'IPI'=A='I'+LE1
      CALL BUTFLY ; PERFORM BUTTERFLY
      MOV A,E ; A='I'
      ADD C ; A='I'+LE
      CPI N ; COMPARE 'I' WITH N
      JP SKIP1 ; IF 'I' > N EXIT LOOP
      JMP ABC ; STAY OTHERWISE
SKIP1: CALL ITER ; CALCULATE U=U*W
      INR D ; 'J'='J'+1
      MOV A,B ; A=LE1
      CPI D ; COMPARE 'J' WITH LE1
      JP SKIP2 ; EXIT LOOP IF 'J' > LE1
      JMP BCD ; STAY OTHERWISE
SKIP2: LDA LL ; A='L'
      INR A ; 'L'='L'+1
      CPI LMAX ; COMPARE 'L' WITH 'LM'
      RP ; RETURN IF 'L' > 'LM'
      JHP CDE ; STAY IN LOOP OTHERWISE
;
; * THE FOLLOWING MULTIPLIES THE COMPLEX NUMBERS ADDRESSED BY HL *
; * (CALLED X=A+BP*SQRT(-1)) BY Y=AP+BP*SQRT(-1) ADDRESSED BY DE. *
; * Y IS IN A COMPLEX ACCUMULATOR IN MEMORY, LOCATION ACCR. *
; * WE HAVE Y=X*Y=(A*AP-B*BP)+(A*BP+AP*B)*SQRT(-1) *
;

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MULT:  PUSH      H      ; SAVE ADDRESS OF X
        MJC       C,M    ; LOAD BC REGISTERS WITH REAL PART
        INX       H      ; OF X.
        MOV       H,M    ;
        INX       H      ;
        XCHG      H      ;
        LHLD      ACCR    ; SAVE X IMAG. ADDRESS IN DE
        CALL      MUL16   ; PUT REAL PART OF Y IN HL. HL=AP
        XCHG      H      ; HL=A*AP
        MOV       C,M    ; MOVE A*AP INTO DE AND ADDRESS OF X IMAG.
        INX       H      ; PART INTO HL. MOVE X IMAG. PART, B, INTO
        MOV       B,M    ; BC REGISTERS. BC=B
        LHLD      ACCI    ; HL=BP (IMAG. PART OF Y)
        CALL      MUL16   ; HL=HL*BC OR HL=B*BP
        MOV       A,E     ;
        SUB       L,A     ; START SUBTRACTING ; HL=DE-HL
        MOV       A,D     ; THAT IS HL=A*AP-B*BP
        SBB      H,A     ;
        XCHG      H,A     ;
        LHLD      ACCR    ; START PUTTING REAL PART OF Y IN DE,
        XCHG      ACCR    ; BEFORE STORING COMPUTED REAL PART
        SHLD      H      ; IN ACCUMULATOR.
        MOV       C,M    ; STORE A*AP-B*BP INTO COMPLEX ACC, REAL PART
        INX       H      ; RESTORE X REAL PART ADDRESS
        MOV       B,M    ;
        INX       H      ;
        MOV       H,M    ; MOVE XREAL PART, A, INTO BC REGISTERS
        PUSH      B      ; HL NOW POINTS TO IMAG. PART OF X. B.
        MOV       C,M    ; SAVE REAL PART OF X, A, ON STACK
        INX       H      ; MOVE IMAG PART OF X, R, INTO BC REGISTERS.
        MOV       B,M    ;
        XCHG      H,M    ;
        CALL      MUL16   ; DE, WHICH CONTAINED AP, IS MOVED TO HL
        XCHG      H,M    ; HL=HL*BC, OR HL=AP*B.
        LHLD      ACCI    ; DE=AP*B.
        MOV       B      ; HL=BP.
        CALL      MUL16   ; RESTORE X REAL PART, A, INTO BC REGISTERS.
        MOV       D      ; HL=HL*BC, OR HL=A*BP
        SHLD      ACCI    ; HL=HL+DE, OR HL=A*BP+AP*B.
        RET            ; ACCUMULATOR=X*Y=(A*AP-B*BP)+(A*BP+AP*B)*I

```

```

* THE FOLLOWING ROUTINE CALCULATES:
*
*   T=A(I)*U
*   A(IP)=A(I)-T
*   A(I)=A(I)+T
* FIRST THE ADDRESSES OF A(IP) AND A(I) ARE OBTAINED FROM
* REGISTERS A=IP AND E=I RESPECTIVELY. BC WILL POINT TO A(I)
* AND DE WILL POINT TO A(IP).

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BUTFLY:

| | | | |
|------|---------|---|-------------------------------|
| PUSH | B | : | |
| PUSH | D | : | |
| PUSH | PSW | : | |
| MOV | H,0 | : | PUT E INTO L AND 0 IN H. HL=E |
| MOV | L,E | : | |
| LXI | D,XTABL | : | LOAD DE WITH XTABL. |
| DAD | H | : | HL=2*HL, OR HL=E+E |
| DAD | H | : | HL=2*HL, OR HL=4*E |
| DAD | H | : | HL=XTABL+4*E |
| MOV | B,H | : | MOVE HL INTO BC |
| MOV | C,L | : | BC NOW POINTS TO A(I) |
| MOV | H,0 | : | LOAD HL WITH ACC. |
| DAD | H | : | HL=2*HL, OR HL=2*A |
| DAD | H | : | HL=2*HL, OR HL=4*A |
| DAD | H | : | HL=XTABL+4*A |
| XCHG | D | : | DE NOW POINTS TO A(IP) |

DE POINTS TO A(IP), BC POINTS TO A(I), T IS IN THE COMPLEX
ACCUMULATOR IN MEMORY WHICH IS ADDRESSED BY BC.

| | | | |
|------|-------|---|--|
| PUSH | D | : | SAVE A(IP) ADDRESS ON STACK |
| PUSH | B | : | |
| LHLD | OR | : | |
| SHLD | ACCR | : | MOVE U INTO ACC. |
| LHLD | UI | : | |
| SHLD | ACCI | : | |
| XCHG | | : | HL POINTS TO A(IP) |
| CALL | CMULT | : | COMPLEX MULTIPLY A(IP) BY U. ACC=A(IP)*U |
| POP | B | : | RESTORE BC |
| POP | D | : | RESTORE ADDRESS OF A(IP) |
| PUSH | B | : | SAVE ADDRESS OF A(I) |
| LHLD | ACCR | : | START CALCULATING A(IP)=A(I)-T |
| LDAX | B | : | THE REAL PART OF A(I) POINTED TO |
| SUB | L | : | BY BC IS SUBTRACTED FROM T IN THE |
| STAX | L | : | ACCUMULATOR AND STORED IN THE REAL |
| INX | D | : | PART OF A(IP) POINTED TO BY DE. |
| INX | B | : | THE SAME IS DONE FOR THE IMAGINARY |
| LDAX | B | : | PART. |
| SUB | L | : | |
| STAX | L | : | |
| INX | D | : | |
| INX | B | : | |
| LHLD | ACCI | : | DO SAME FOR IMAGINARY PART. |
| LDAX | B | : | |
| SUB | L | : | |
| STAX | L | : | |
| INX | D | : | |
| INX | B | : | |
| LDAX | B | : | |
| ADD | L | : | |
| STAX | L | : | A(IP)=A(I)+T |
| POP | B | : | RESTORE ADDRESS OF A(I) |
| LHLD | ACCR | : | LOAD HL WITH REAL PART OF T |
| LDAX | B | : | START CALCULATING A(I)=A(I)+T |
| ADD | L | : | |
| STAX | L | : | STORE BACK INTO A(I) |
| INX | D | : | |
| INX | B | : | |
| LDAX | B | : | |
| ADD | L | : | |
| STAX | L | : | |
| INX | D | : | |
| LHLD | ACCI | : | DO FOR IMAGINARY PART ALSO |
| LDAX | B | : | |
| ADD | L | : | |
| STAX | L | : | |
| INX | D | : | |
| INX | B | : | |
| LDAX | B | : | |
| ADD | L | : | |
| STAX | L | : | A(I)=A(I)+T |
| POP | PSW | : | RESTORE ALL REGISTERS |
| POP | H | : | |
| POP | H | : | |
| RET | | : | RETURN |
| END | | : | |

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